For Residen

Volume II: Tech

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VOLUME II

INTERIM TECHNICAL REPORT

FIRE SAFETY SYSTEMS

ANALYSIS FOR RESIDENTIAL

OCCUPANCIES:

TECHNICAL SUPPLEMENT

March 1977

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LIST OF ABBREVIATIONS

BFM - Building Firesafety Model

DT - Decision Tree

FDM - Fire Development Model

FSOC - Firesafety Objective Component(s)

FSOCL - Firesafety Objective Component Logic

GSA - U. S. General Services Administration

HRM - Human Response Model

HUD - U. S. Department of Housing and Urban Development

MPS - Minimum Property Standards

NFPA - National Fire Protection Association

PCL - Parameter Conversion Logic

P_F - Probability of Failure

P_{FSOC} - Probability of Achieving Firesafety Objective Compo

POC - Products of Combustion

POCM - Products of Combustion Model

This report details the development of a model for estimating comparing the levels of fire safety for alternative design con- urations. The model is designed to permit estimation of equiva- cy* of firesafety levels obtained from design alternatives to t . Department of Housing and Urban Development Minimum Property ndards (HUD/MPS). The model was developed using the systems ap ach, whereby the interaction of all the structural components a sidered rather than individual component specifications. In or demonstrate the feasibility of the systems approach, a test was eloped using the MPS for One- and Two-Family Dwellings (4900.1) approach will later be extended to the MPS for Multifamily Hou 10.1)[5], Care-Type Housing (4920.1)[6], and the Federal Mobil e Construction and Safety Standards[7].

The heart of the systems approach is a fire development model ch simulates fire growth utilizing a state transition model. H avior is also simulated as well as the interaction of fire beha human response. The addition of building design parameters, f ety objective components, and products of combustion result in plete interactive model which is termed the Building Firesafety el (BFM).

The BFM is briefly described in Volume I and described in mor

plains how the BFM and the systems approach are related. Al

in the report are the results of the test to demonstrate the

of approach. Finally the relationship of the MPS to the sys

proach is discussed.

EXECUTIVE SUMMARY

This report details the findings of Phase I of a t which is being conducted to develop a systems approach of the relative firesafety levels of alternative desigr especially with regard to the establishment of equivale Department of Housing and Urban Development's Minimum F (HUD/MPS) for residential occupancies.

Volume I is a report to "users." Included as "use

- HUD officials - the acceptance authorities u systems approach and the equivalency tests
- Designers - the architects and engineers of

Readers are invited to correspond with the project sta tential uses and important design alternatives to be i

Volume II of this report is written primarily for fire protection engineers who wish a more detailed tec of the model, the simulation process, and this particu state transition models. It is hoped that the data co help others in planning their research efforts and enc dialogue.

cision Tree (DT) (Figure 1-1)[1] was used. The DT is based on
ring work of the U.S. General Services Administration in the s
ea.[2] It has been assumed in the research that the DT repres
e important factors in the prevention and control of building

Efforts to utilize the Decision Tree resulted in many probl
s direct application. These problems stemmed from a lack of s
the DT elements which in turn led to an inability to formulat
national mathematics of the Tree. This conclusion in and of i
important finding of the study since it had been assumed that
uld be directly applied.

The result of the inability to apply the Tree directly requ
velopment of a computer model of fire growth and development b
e systems approach. The computer model is based on a state tr
del of fire growth which breaks up the fire development into s
ates, called "realms," and assigns a set of rules by which the
esses from one realm to another. This model is broken down in
mponents, each of which simulates a different portion of fire
nt. These components are:

- fire spread

These tests involved the reaction of the model to varying typ

ior finish. In these sensitivity tests the computer model re

dictably, which is an indication that this model works as ant

The sensitivity tests were also used as the basis for a

plication of the products of this contract to the evaluation

design. In this example, the cost versus firesafety issue wa

The example only utilized a change in a single factor but it

cate how one of the model outputs may be used.

Throughout Phase I, an extensive literature search was c

collect supporting data for the problem analysis and the mode

As an aid to those who are working in the field, a literature

cluded in Appendix D of Volume II. A discussion on the metho

this literature search appears in Appendix C, Volume II of th

In summary, the results of this phase of the study are:

- The development of a systems approach to the evalu

  fire safety

- A computer simulation to provide quantitative eva

  of fire safety

- A demonstration of the feasibility of this system

ACKNOWLEDGEMENTS

The work presented here could not have been completed without t
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 Wood, Philip H. Thomas and Richard E. Stevens, the members of
Systems Concepts Committee, and many of the personnel in HUD ha
ill continue to be of great help.

CHAPTER I

INTRODUCTION

A quantitative measure of fire safety indicating the degree
fety for people in a building, for the building, and for the bu
contents, is an essential requirement for those professions c
h fire protection responsibilities. Fire safety is usually an
re and complicated function of many factors including fire pre
n, fire growth, fire suppression, and human behavior. Such fa
lude all of those associated with the life of the building fro
n through construction and, finally, to building use. The exp
developing a quantitative measure is that it will permit econo
ign (or redesign) of buildings with an appropriate level of fi
ety, since the measure will allow knowledgeable design options
t/safety factors.

The purpose of the study discussed in this volume is to eval
ticular building standard, the Dept. of Housing and Urban Deve
D) Minimum Property Standards (MPS). This evaluation is to be

luation of the Decision Tree

In order to organize a systematic approach to the quantitativ sessment of fire safety, the National Fire Protection Associatio FPA) Systems Concepts Committee developed a logic tree which del ates the relationships of fire protection system elements. The sion Tree* (DT) in its present form (1974 edition) incorporates e believed to be all possible factors for preventing or controll res. The Tree serves as a framework for the development of a qu tative evaluation of fire safety. However, application methodol the DT to the direct evaluation of fire safety in particular bu g types has proven difficult.

The difficulty stems from the structure of the Tree, as well e nature of the elements. The elements in the tree are general ture (lack specificity) and, therefore, are difficult to assign ilities to directly. For instance the element entitled "Contai d/or Confine Fire" is not an event but a collection of possible amples of these elementary events would be whether doors and wir e open or closed, or whether a heating, ventilating, or air conc stem is operating. These events can be assigned probabilities b ee does not delineate which of these elementary events correspor

estimating the relative contributions of the various events.
ent tree does not do this.

The structure of the Tree also presents a problem. The Tree
ady been described as a success tree which is a static solutio
problem. That is, whenever some level of success is achieved b
combinations of elements, a specific level of fire safety wil
hed. Fire growth and development is a time-oriented process a
uch many objectives may not be met (such as attaining life saf
though at some point later in the fire all the DT elements ne
reach this goal may be fulfilled. By using a tool which is dyn
esign, it is possible to develop a method which will assign we
he elements in the tree and also consider the effects of combi
s of elements and combinations of events.

Finally, Boolean logic implies that only certain paths are nec
eet the objectives of the success tree. This may well not be t
other paths, not indicated by Boolean logic, may prove even mo
rtant. That is, Boolean logic may be the wrong model for combi
elements of the DT.

This discussion of the difficulties of direct application of
sion Tree does not mean to imply that the DT is invalid or tha

Therefore, our research team has developed a dynamic moc the DT elements with the intent of learning how these element be combined when estimating levels of success in meeting fire objectives. However, the research team holds open the final as to whether or not the Boolean logic of the DT must be alte better describe how the elements combine to produce various l fire safety.

Fire safety is defined in terms of components for which proba
tements and probability values can be determined. The followin
esafety Objective Components (FSOC) have been established:

1. Life safety for people who are capable of self-preservati
2. Life safety for people who are nonambulatory, infantile, senile, or otherwise incapable of self-preservation.
3. Protection of structure (building).
4. Protection of utilitarian value of facility (mission).
5. Protection of contents of structure.
6. Protection of community (i.e., of community exposure from effects of a fire in the structure).

Assume for a moment that methods of applying the DT are known
en the capability, how could the HUD/MPS be evaluated? One way
gested in Figure 1-1 in which the influence of the MPS on build
ameters is determined and a set of building parameters satisfyi
MPS are input to the DT. As illustrated in Figure 1-1, probab
es of satisfying firesafety objectives (P_{FSOC}) are determined u
Tree. With this concept, a building design consistent with th
can be evaluated with regard to fire safety.

The effect on fire safety of one or more MPS specifications c

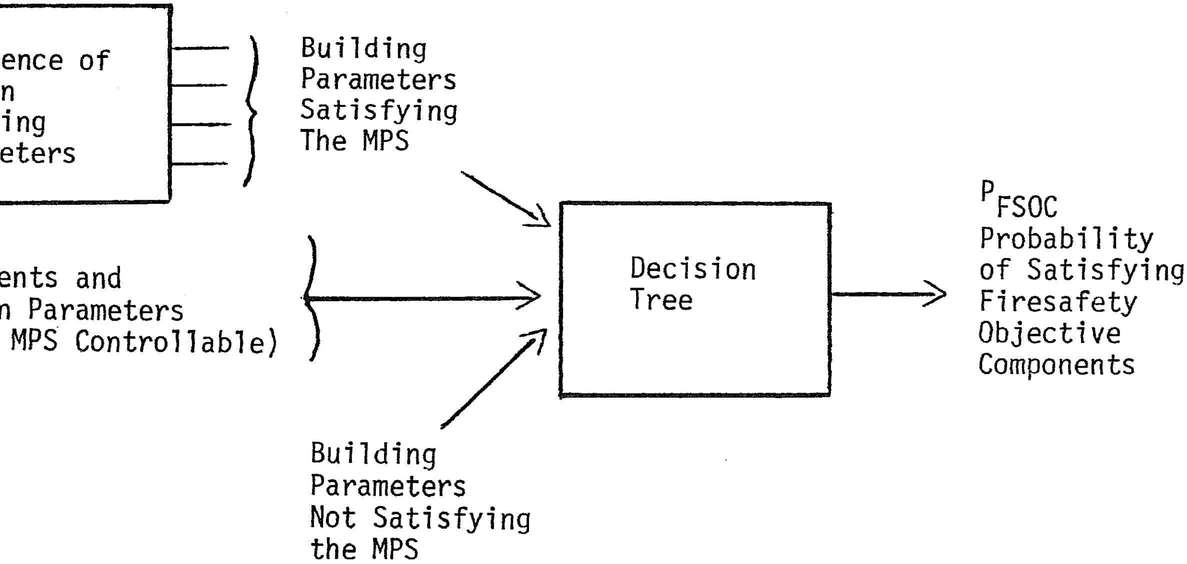


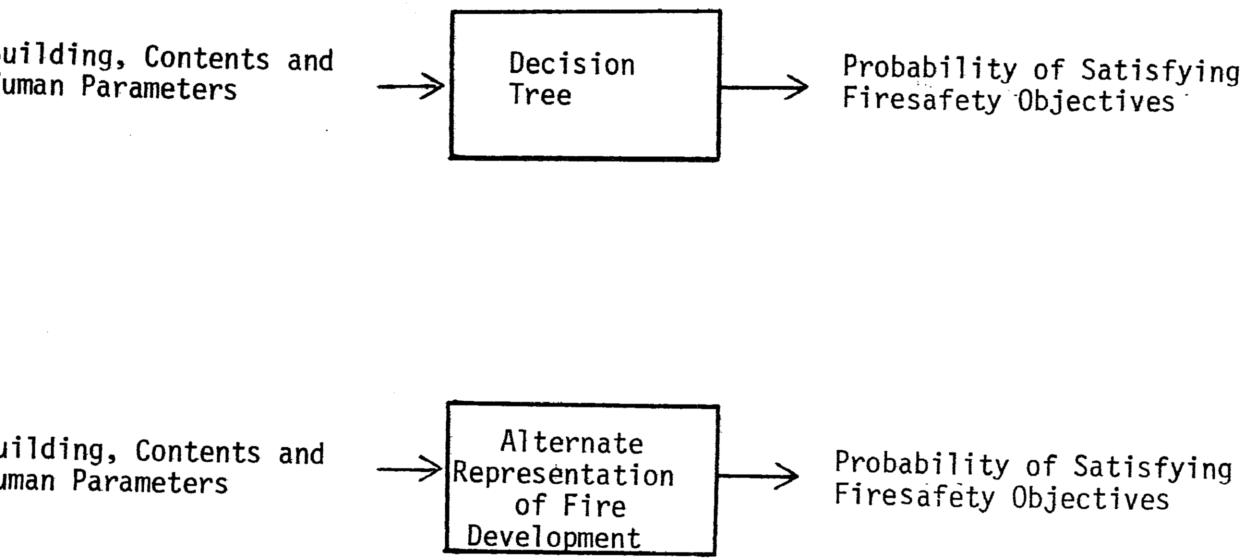
Figure 1-1 Method of Evaluating MPS

from that obtained when there was no MPS violation.

e problem then is to develop a method for applying the DT.

order to solve the problems in applying the DT discussed pre-, an alternative representation of fire development as suggeste 1-2 must be developed. This alternative representation must the same inputs (building, contents, and human para- and provide the same outputs (P_{FSOC}) as the Tree. Analysis alternative representation can show how to use the Tree. Per- can show how to revise the Tree to make direct application pos- This alternate representation is termed "Decision Tree Model"

ere are several similarities between the DT and the DTM. Most ntly, the inputs and outputs are somewhat similar. Inputs to are, at the present time, parameter categories (e.g., provide for ventilation); inputs to the DTM are the quantified vari- e.g., total window area = 10ft^2) of those categories. The majo that the internal logic of the DT is general while the logic o is specific to a given occupancy type. Thus, the DTM logic n effect, be that of the DT with any irrelevant logic removed.


uilding, Contents and
uman Parameters
Decision
Tree
Probability of Satisfying
Firesafety Objectives
uilding, Contents and
uman Parameters
Alternate
Representation
of Fire
Development
Probability of Satisfying
Firesafety Objectives

Development of a DTM for a specific application requires da

uantitative answers to questions. Such questions concern the e

f fire development, the amount and dispersion of the combustion

cts, and the interactive impacts of people and fire. Since no

lete theory or data base is available to answer these specific

ions, a means is necessary to represent what is known about fi

amics. A Building Firesafety Model (BFM) representing fire dev

ent, combustion products generation and movement, and the inter

ffect of people and fire can satisfy this need. With the BFM,

fic types of fires can be represented in specific types of occu

nd questions as to probability of a given extent of damage and

ility of injury or death can be answered.

What is the difference between a DTM and BFM? The answer

ailed in the description of the BFM presented in Chapter 2. Es

ially, the BFM is a dynamic computer model and represents many

unctions of fire growth and spread. In contrast, a DTM is a se

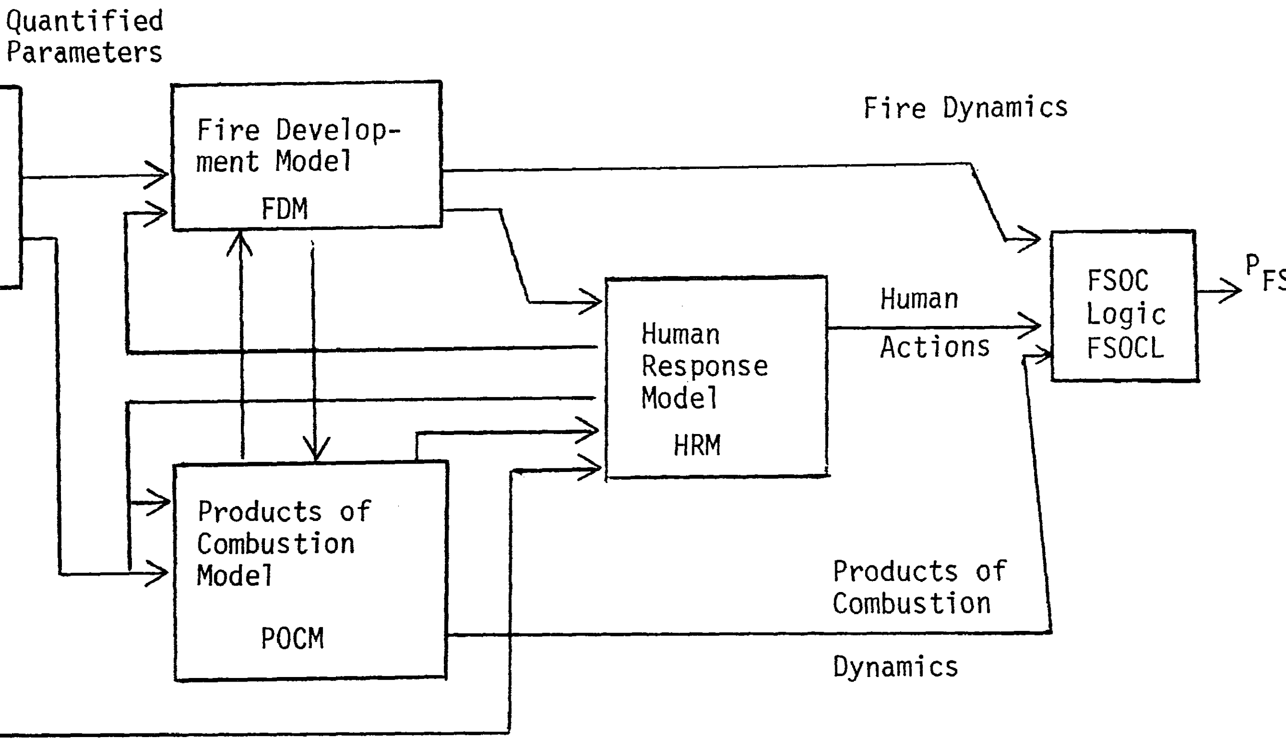
lgebraic equations (or tables and graphs) representing the rela

hip between building parameters and P_{FSOC}.

A block diagram of the BFM is shown in Figure 1-3. This di

ncludes several component models and logic:

Property Conversion Logic (PCL)


Quantified Parameters
Fire Development Model
FDM
Fire Dynamics
Human Response Model
HRM
Human Actions
FSOC Logic FSOCL
P_{FS}
Products of Combustion Model
POCM
Products of Combustion Dynamics

opment Model represents fire growth and spread while the Produc Combustion Model represents generation and spread of smoke, hea l gases. The Human Response Model represents the action of peop volved in the fire - including the effect of people on the fire velopment. The FSOC logic accepts inputs from each model and de nes the probability of success for each firesafety objective com t. Evaluation of a particular building design would proceed wit putting building and furnishing parameters, and information abou e individuals in the building. The output of the models would b lculations of P_{FSOC} values.

The parameter conversion logic relates a building design to p ble fire initiation, growth, and spread. Such logic can be deve om several sources:

- fire incident data
- fire test data
- case histories
- fire theory
- professional judgement of fire protection engineers
- combinations of the above factors.

e conversion logic can be specific and apply only to one buildir can be general and apply to a class of building types. Ideally

art of the BFM and consistent with the purpose of the BFM, the lo
esents what is known about fire development as a function of bui
ents, and human parameters. On the other hand, if there is uncer
use of varying burning rates, then a distribution of fire develop
meters for given sets of human, contents, building parameters mus
ped and the parameter conversion logic must represent this distri

Fire Development and Human Response Models were developed and e
d in the Phase I effort. These models are described in detail i
subsequent chapters of this report.

The first step in FDM construction is to identify significant c
ons of the fire development, such as "first material (only) invo
room of origin fully involved." A complete set is discussed in
ter 2. Dynamics of the fire development are represented by the
t of time a certain condition exists and the probability of chan
one condition to another. These dynamics are determined by the
acteristics of the fire environment. Also represented is the ef
uman actions on fire, e.g., manual suppression by people involve
fire or fire department personnel.

The HRM was developed in an analogous way in which the human lo
and actions are represented along with the change in location a

t is included in Appendix D of this volume. A discussion on the nodology of this literature search appears in Appendix C of this ume.

eptual Description of the Models and Their Potential Use

A model merely represents what is known about a subject. If th ue of a variable is known, the value is entered into the model. value is not known but its distribution is known or can be estim that distribution can be entered into the model, and so forth. of the model allows one to ask questions and get answers which r ent, to the degree the model represents the real situation, the a the questions posed. In this sense, the models provide an "accou lly of the result of combinations of complex factors which are r easily envisioned without the model. It is the accounting or mar tion of the data which makes the model useful. For instance, to atively evaluate the effect of a particular factor or to estimate efits from a proposed solution.

In the case of the Fire Development Model (FDM) to be describe objective is to represent in a very simple form each of the fact ch are believed to affect fire development. The lack of an overa e development theory and the spottiness of data suggests that a ble type of model should be utilized for at least the initial inv ations.

ia for that realm as opposed to changing to conditions which sa

ther realms.

ire conditions selected for one/two family homes are as fol-

- no fire
- first material is involved
- second material is involved
- room is fully involved
- second room is involved
- floor of origin is fully involved
- floor beyond origin is involved (in dwelling of origin)
- dwelling is fully involved

he occurrence of a critical event has long defied prediction.

er for the model to simulate fire development, a non-determinis

(a deterministic model accepts as input a set of initial condit

uniquely determines the output) had to be developed. Probabili

provided a possible solution. In a probability based (or stoc

model, the changes from realm to realm are called transitions

signed a probability (likelihood of occurrence). For instance,

n which the second material has become involved might have a pr

fore a critical event occurs which demands a change in realm. These
an times are directly related to a particular transition. For examp
e mean time for a transition from the second material involved (real
to full room involvement (realm 3) might be five minutes while the
an time for a transition from the second realm to the first realm
irst material involved) might be one minute.

In order to determine the transition probabilities and mean realm
mes, several routes can be taken. Experimental data and professiona
dgement all play a part. However, the probabilities and mean times
re not directly available so judgements as to the distributions of
alm times and transition probabilities had to be made. For realm t
e times were distributed according to a geometric distribution. Pr
ssional judgement was used to generate transition probabilities.

An example of how the transition probabilities and mean realm ti
e used may be useful. In a room fire the temperature grows for a
riod of time, reaches a peak and, if the fire has not spread to new
els, finally drops off. Test data often yields a temperature histo
at is symmetric about the peak. This would lead us to the conclusi
at a fire, where only the first material was involved, would have n
ual probabilities of transition to a second material and to self-ex
ishment. However, the mean times for transition to the second mate

ple in attempting to suppress fire, changing the configuration o building (e.g., closing a door) communicating with other people ners in the building, notification of fire department, etc.), ar ement of people can be modeled.

The coupling between one part of the model and another, such a effect of the portion representing human actions on the portion resenting fire development, is included by representing the effe the human actions on the realm transition probabilities. Likewi effect of a human response on a fire is represented by the effe the probability that the human will select a certain initial act follow it by another action. For example, given that only the erial is involved (a small fire), there is a relatively large pr ity that humans will respond to the fire site, then obtain supp tools, then attempt suppression. But, given a large fire, tha ability will certainly decrease.

Operation of the model proceeds from an assumed initial realm med initial location(s) of the humans involved in the fire. An e operation commences in which, for each successive time interv fire development (realm transition) and human response (actions lated according to the probability distributions established. sitions include the effect of one part of the model on the othe

ent will follow the rules established by the time distributions a
nsition probabilities as affected by the interaction of one port
the model with another. However, we are not interested in exami
development, i.e., one "movie," but instead, are interested in
ng the statistics of many likely developments. For example, one
ety objective component involves the damage to the building. Fo
n type of fire initiated, the amount of damage to the building m
identified by the extent of fire growth in the building. Thus,
bability that the fire development will exceed a certain growth
computed directly from multiple runs of the Fire Development Mod
this way, the effects of variations of any variable on achieving
cess in any firesafety objective are computed.

Applications of such a model, which is a very simple model, ca
y extensive. The application of interest here is the evaluation
babilities of success of achieving each firesafety objective as
hod of determining the firesafety level of a design or structure
ever, the BFM can be applied to many other areas. For instance,
ld be used to evaluate the impact of a new firesafety standard.
BFM can be adapted to the distributions of fire developments i
iven community (conflagration potential). Also, the BFM can be

ponses that affect fire development are discussed in the next se n and a combined model is described in a later section.

The purpose of the FDM is to establish fire conditions (termed ms) as an aid in computing probabilities of success (P_{FSOC}). E ishing the FDM realm as discrete fire conditions has several be s. First, calculation of P_{FSOC} can be accomplished on a realm b m basis - each being a distinct case. Second, the fire dynamic alm time and transition probabilities) can be determined from al ilable data sources. Third, the model concept is easily underst reas the method of calculating realm time and transition probabi be complex. Therefore, this ease of understanding may aid in m espread acceptance and use of the model versus a more abstract a ach.

It is generally agreed that fire development can be divided i lms but that the dynamic fire properties are variable - a functi realm time. For example, the probability of transitioning to a resenting a fire spread may be a function of realm time. How ca ynamic time-changing process be represented by a fixed set of r es and transition probabilities? The answer used in developing el is that the process can be represented to any degree of fidel ired simply by subdividing the realms into sub-realms. In short

- Determine realm times and transition probabilities for each realm

first two steps identified above are described in this section ce realm times and transitions are affected by human actions, t e development variables are established in a combined model.

ical Fire and Fire Location for One- and Two-Family Dwellings.

Information about the types of fires occurring frequently in l two-family dwellings is required for input to the fire develop l human response models. Specifically, the types and locations res, frequency of occurrence, and location of people at time of tion, etc., are required.

A set of fire types is shown in Table 2-1 and is used as a wo t. Also indicated is the relative location of the fire and dwel cupants.

Both flaming and smoldering fires were considered in each of elve fire scenarios. These two fire types have different effect e mean time for transitions between early realms. The mean will cording to the type of fire being considered. For example, in a droom fire (type 10), the mean time for a transition from realm alm 2 is 3 minutes for a flaming fire. When considering a smolc

Location of Ignition in Dwelling	First Material Ignited	Location of Dwelling Occupants of Ignition			
		Area of Origin	Room of Origin	Exit	Flo Ori
Basement	Wood, Paper				
Basement	Wood, Paper			X	
Bedroom	Wood, Paper	X			
Bedroom	Wood, Paper		X		
Bedroom	Wood, Paper				
Kitchen	Fabric	X			
Kitchen	Fabric		X		
Kitchen	Fabric			X	
Bedroom	Fabric	X			
Bedroom	Fabric		X		
Kitchen	Food	X			
Kitchen	Food		X		

ead and the probabilities of transition from one realm to anothe
ection of realms is influenced by data availability and the purp
the model - only those realms required for calculating the P_{FSOC}
ieving firesafety objectives need be defined.

Realms exist for a time interval and begin with an event terme
itical event." A critical event occurs at the first instant a s
ed fire condition is satisfied. A critical event is used furthe
ntify the fire condition necessary for the start of a realm. Th
tinued existence of a realm depends on whether or not the fire c
ion satisfied criteria for possible subsequent realms.

Fire conditions selected for one- and two-family homes were as
lows:

- No fire
- First material is involved
- Second material is involved
- Room is fully involved
- Second room is involved
- Floor of origin is fully involved
- Floor beyond origin is involved (in dwelling of origin)
- Dwelling is fully involved

consider the three possible combinations of first and second mat
involved in fire:

- First material involved and not the second,
- First and second material involved
- Second material involved but not the first.

Depending on the purpose of the model, one, two, or three realm
be defined to represent the two-condition fire involvement proce

A logic to convert the conditions to describe fire realms r
three functions: "true," "false," "don't care." As defined in
2-2, logic for each realm specifies that certain conditions be t
false, or that the logic "does not care" if the condition is tru
false. For example, the logic for Realm 0 (no fire) requires th
conditions be false. While the logic for Realm 2 requires that
material involved" be true and all other conditions be false exc
first material involved." The logic "does not care" applies to "f
material involved."

Figure 2-1 illustrates a likely fire realm sequence where t
no automatic or human detection of fire and, therefore, no suppr
activity initiated. The figure illustrates the transitions that
likely to occur from one realm to another by arrows. For exampl
transitions from Realm 3 (Room is Fully Involved) are to Realm 4

ne Fire Development Model.

ealms	1st Material is Involved	2nd Material is Involved	Room of Origin is Fully Involved	2nd Room is Involved	Floor of Origin is Fully Involved	Floor Beyond is Involved
0	0	0	0	0	0	0
1	1	0	0	0	0	0
2	-	1	0	0	0	0
3	-	-	1	0	0	0
4	-	-	-	1	0	0
5	-	-	-	-	1	0
6	-	-	-	-	-	1
7	-	-	-	-	-	-

0 False

1 True

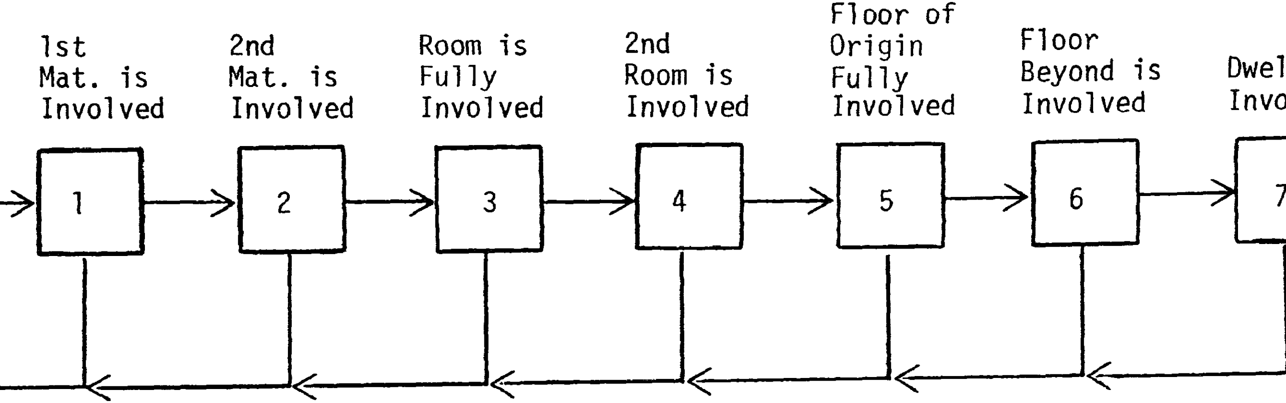


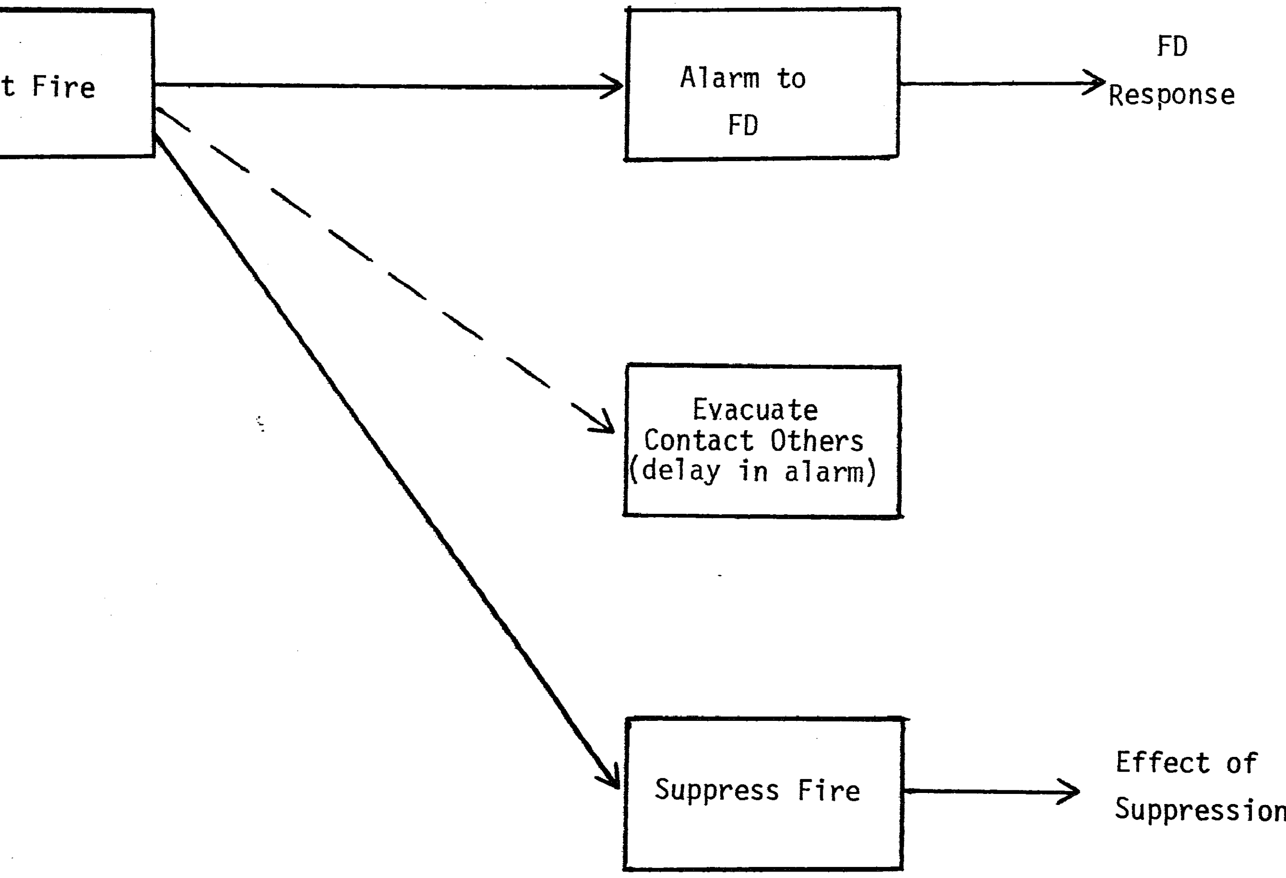
Figure 2-1   Likely Transitions for One/Two Family Dwellings

The dynamic interaction of humans and fire development is
way process in which humans affect the ignition and growth of
and fire and combustion products affect humans. These two ef
described separately in the models of human response (HRM).
fect of fire on humans depends in part on the relative locati
fire to the persons. The HRM is therefore developed to repre
actions of all individuals involved in the fire.

In order to represent the effect of human actions on fir
sider a simple model of the actions of the first individual d
the fire, illustrated in Figure 2-2. The set of possible fir
is taken as: Suppress Fire, Evacuate, or Alarm to Fire Depa
An alternative "take no action" was classified as "no detecti
that portion of the HRM representing the impact of humans on
Also, if an individual evacuates without attempting fire supp
without notifying the fire department either before or after
with respect to fire development, those actions can also be cl
as a "no detection."

"Alarm to Fire Department" can be taken to include notif
a first action and also notification after evacuation. As a
effect of the human response on the fire is modeled with two

- Alarm to Fire Department


t Fire
Alarm to FD
FD Response
Evacuate Contact Others (delay in alarm)
Suppress Fire
Effect of Suppression

The model presented above can be expanded to form a more com

ve model reflecting the activity of all individuals involved in

re. This includes the actions of the individual(s) affecting t

described above. As shown in Figure 2-3, the first action of

viduals who detect the fires, are alerted to the fire, or are a

the fire is represented as one of the following:

- Evacuate
- Attempt Fire Suppression
- Send Alarm to Fire Department
- No Activity

te that "No Activity" is similar to not being alerted, not dete

not reporting the fire.

Second actions stem from the first. For example, an individu

n either evacuate without giving the alarm or can evacuate and

tify the fire department. This latter condition is combined wi

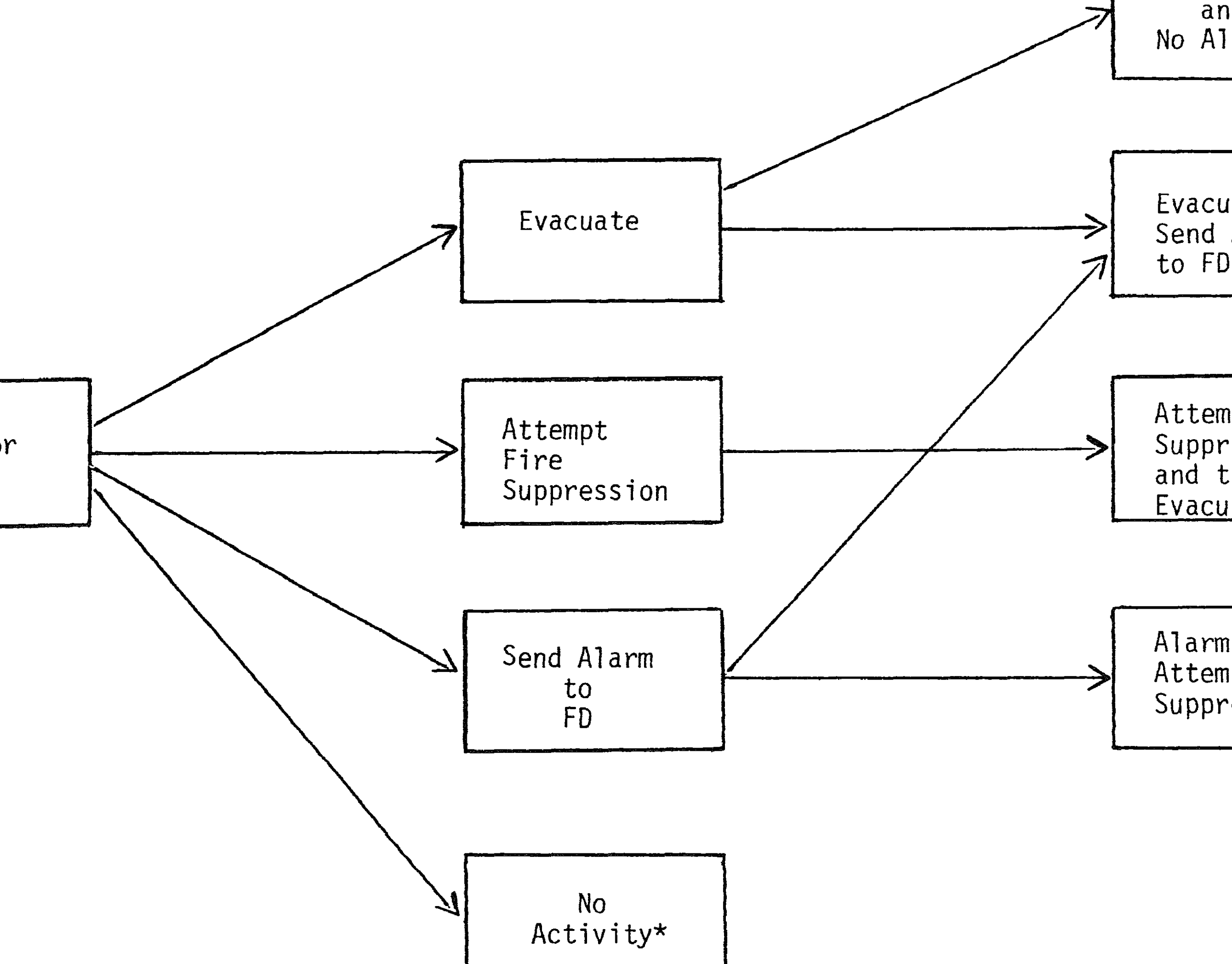
tifying the fire department and then evacuating as discussed in

evious paragraph. Alternatively, the individual can evacuate a

tempting fire suppression which may or may not have been succes

the fire suppression is successful, the fire realm changes to

re." If the individual attempts fire suppression and then evac



or
Evacuate
Attempt
Fire
Suppression
Send Alarm
to
FD
No
Activity*
an
No Al
Evacu
Send
to FD
Attem
Suppr
and t
Evacu
Alarm
Attem
Suppr

ocation of the individual with respect to the fire and the exist ire realm. A set of relative locations includes the following:

- room of origin
- floor of origin
- exit
- floor beyond room of origin
- other dwelling unit
- outside dwelling of origin

elation of Model and Decision Tree "Manual Suppression" Branch.

The HRM described above employs logic from the "manually sup ire" section of the Decision Tree (DT). The DT identifies six a hich are combined by AND logic to designate the actions required anually suppress a fire. These actions are:

- detect fire
- communicate signal
- decide action
- respond to site
- initiate suppressant
- control fire

The HRM described above uses only some of the responses as i

sant" of the DT are combined in the modeled human action: Notif

epartment. Thus, the logic for manual fire suppression, as

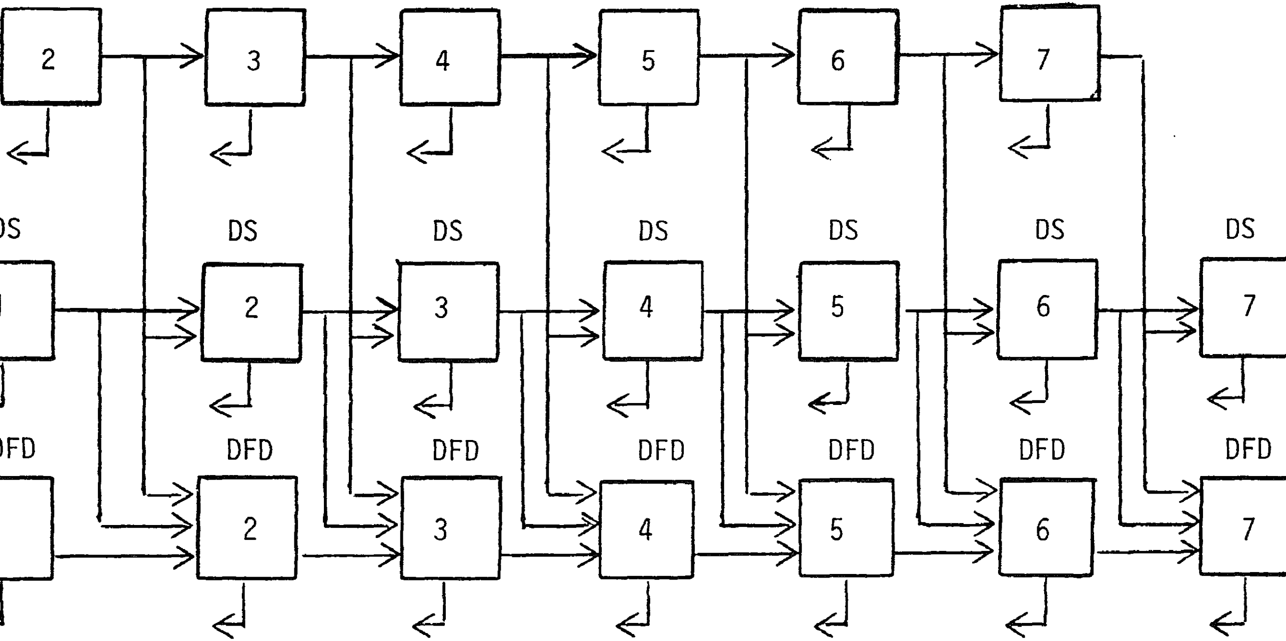
ed by the Decision Tree, is used directly in the Human Response

The models for fire devleopment and human response described
he previous sections can be combined to represent fire developme
xtinguishment with human intervention in one- and two-family dwe
fixed FDM structure, as defined by the realms selected, is requ
o represent types of fires (as defined in Table 2-1), but some m
ariables (realm time distributions and transition probabilities)
djusted to represent fire development for each combination of fi
nd fire location.

In order to represent the effect of human actions on the fir
ire realm is combined with human actions to include the effect o
etection, fire department response, and occupant suppression. Fo
s shown in Figure 2-4, the realm/action combinations associated
he "First material involved" are:

- First material involved, fire not detected
- First material involved, fire detected, and manual suppression initiated by occupant
- First material involved, fire detected, and the fire department responded

he set of realm/action combinations associated with the "Second
nvolved: are:



$\overline{D}$ No Fire Detection

DS Detection and Occup.

DFD Detection and Fire D
Responded

ved at that realm. For example, a room fire occurs when all fuel e room are involved with the flame. Once a room fire is establis s properties are independent of the way the fire was initiated. operty of fire suggests the modeling approach used in which fire lopment is represented by realms and realm transition probabiliti

The variables of a realm are the time distribution of that rea l probabilities of transition to other realms. For example, cons alm/action combination 2DFD (as identified in Figure 2-4) which i econd material involved, fire detected, and fire department respo establishing that combination, it is claimed that once the realm tered, the properties of that realm, i.e., the transition probabi om the realm and the time the realm exists, are independent of pr ous realm. It is also claimed that the next transition is indepe the time spent in the realm. Thus, realm/action sequence 0-1$\bar{D}$-2 FD leads to the same situation as sequences 0-1$\bar{D}$-1DS-2DFD or 0-1$\bar{D}$ FD. It is assumed that aggregating data from all sequences leadi alm/action combination 2DFD is a reasonable way to compute the pr es of that combination.

Combinations selected for modeling are believed to be reasonab least for an initial effort. If it is found that transition pro

rameter Conversion Logic

Parameter conversion logic translates building parameters into re development and products of combustion parameters. In a sense translates the real world of building and living practices into del of fire in a building. As suggested previously, the plan is velop the logic from fire test data and theory, validated with f ta - fire department experience data. Where necessary, voids in ta will be overcome using professional judgement.

Since development of a data-based logic is to be completed du e Phase III portion of the project, an initial "cut" was provide professional judgement. In order to provide a suitable format dgement estimates of realm time and transition probabilities, va mbinations of the fire development realms and human actions were d estimators asked to identify suitable probability estimates. ndbook was formed providing instructions and data sheets for the mators. The following sections are extracts from that handbook t, instead of enclosing blank data sheets, as was the case for t iginal handbook, completed data sheets for two sample fires - a tchen fire (Tables 3-1a and 3-1b) and bedroom fire (Tables 3-2a

ble 2-2 where eight realms are identified. Realm 0 is the "no f
tuation and Realm 1 corresponds to the "first material involved.
nce fire spread may be different for each type of fire, separate
bles are used for each type of fire.

Tables 3-1 and 3-2 are provided in two parts, Section a and
ction b. Section a is for presenting the probability of
ansition from one realm to another. Each fire realm is associat
th a table row. For example, Realm 1, which corresponds to firs
terial involved, is associated with the first row. There are ei
lumns associated with each row where one column per row has been
ossed out, i.e., not to be used. The first column marked "0" is
r the probability of transfer to Realm 0. Similarly, the elemen
e third column under "2" is to be used to enter the probability
ansfer to Realm 2. The column under "1" is crossed out in row o
cause it has no physical meaning, in other words, a transition m
timately take place.

Section b of each table is for recording the mean time the fi
in the present-realm (represented by the row) before transition
the each possible next-realm (represented by a column). If the
obability of transfer from one realm to another (as recorded in

(represented by a row) To Other Realms (represented by each column)

Source of Heat 6.* Kitchen Stove
First Material Fabric
Location of Fire Initiation Kitchen

Realm	Human "Realm"	0	1	2	3	4	5	6	7
1	$\bar{D}$	.70		.30					
2	$\bar{D}$	.70	.25		.05				
3	$\bar{D}$	.001				.99	.009		
4	$\bar{D}$						.75	.24	.01
5	$\bar{D}$							.30	.70
6	$\bar{D}$								1.00
7	$\bar{D}$	1.00							
1	DS	.99		.01					
2	DS	.97	.029		.001				
3	DS	.02				.97	.01		
4	DS						.98	.01	.01
5	DS							.99	.01
6	DS								1.00
7	DS	1.00							
1	DFD	.99		.01					
2	DFD	.97	.029		.001				
3	DFD	.95				.035	.01	.005	
4	DFD	.95					.04	.01	
5	DFD	.93						.06	.01
6	DFD	.80							.20
7	DFD	1.00							

*Type fire defined in Table 1

Mean Time in Each Realm (represented by a row) Before

Transfer to Other Realms (represented by each column)

Source of Heat 6. Kitchen Stove
First Material Fabric
Location of Fire Initiation Kitchen

Human "Realm"	0	1	2	3	4	5	6	7
$\overline{D}$	.25		.75					
$\overline{D}$	2.00	2.00		8.00				
$\overline{D}$	20.00				8.00	9.00		
$\overline{D}$						7.00	8.00	2.00
$\overline{D}$							2.00	10.00
$\overline{D}$								10.00
$\overline{D}$	Burnout							
DS	.25		.5					
DS	1.0			.25				
DS	10.00				7.00	7.00		
DS						10.00	12.00	2.00
DS							10.00	10.00
DS								5.00
DS	Burnout							
DFD	3.00		3.5					
DFD	4.00	4.00		7.00				
DFD	5.00				6.00	8.00	7.00	
DFD	6.00					10.00	9.00	
DFD	10.00						12.00	17.00
DFD	12.00							20.00
DFD	30.00							

Time in minutes

Source of Heat 9.* Cigarette
First Material Fabric
Location of Fire Initiation Bedroom

Human "Realm"	0	1	2	3	4	5	6	7
$\bar{D}$	.80		.20					
$\bar{D}$	.40			.60				
$\bar{D}$	.30				.65	.05		
$\bar{D}$						.95	.05	
$\bar{D}$							.30	.70
$\bar{D}$								1.00
$\bar{D}$	1.00							
DS	.99		.01					
DS	.97	.029		.001				
DS	.02				.97	.01		
DS						.98	.01	.01
DS							.99	.01
DS								1.00
DS	1.00							
DFD	.99		.01					
DFD	.97	.029		.001				
DFD	.95				.035	.01	.005	
DFD	.95					.04	.01	
DFD	.93						.06	.01
DFD	.80							.20
DFD	1.00							

*Type fire defined in Table 1

Mean Time in Each Realm (represented by a row) Before

Transfer to Other Realms (represented by each column)

Source of Heat 9. Cigarette
First Material Fabric
Location of Fire Initiation Bedroom

Human "Realm"	0*	1	2*	3	4	5	6	7
$\bar{D}$	5./20.		3./20.					
$\bar{D}$	5./25.			20.				
$\bar{D}$	20.				3.	7.		
$\bar{D}$						7.	8.	
$\bar{D}$							2.	10.
$\bar{D}$								10.
$\bar{D}$	Burnout							
DS	.25		.50					
DS	1.	.50		3.				
DS	10.				7.	7.		
DS						10.	12.	2.
DS							10.	10.
DS								5.
DS	Burnout							
DFD	3.		3.5					
DFD	4.	4.		7.				
DFD	5.				6.	8.	7.	
DFD	6.					10.	9.	
DFD	10.						12.	12.
DFD	12.							20.
DFD	30.							

*Dual estimates relate to a flaming ignition/smoldering ignition.

The second row is filled out in a similar way except that now the entry under the column marked (2) is crossed out. The first set of rows (1-7) are associated with fires burning without detection ($\bar{D}$). The second set of rows (8-14) are associated with a fire that has been detected and suppression work initiated (DS). Since one or more individuals are engaged in suppression work, the probability of transition from the present realm to Realm 0 might be expected to increase and perhaps, the mean time the present-realm exists prior to transition may change.

Finally, the last seven rows (15-21) represent the fire situation where the fire has been detected and the fire department responded (DFD). Again, one might expect that the transition probabilities and mean realm existence times might be different once the fire department has responded. In each of the three cases identified above ($\bar{D}$, DS, DFD), the realm time of interest is the time the combination fire realm and human realm exists. Thus, we may find that the fire may be in Realm 1 undetected for awhile ($\bar{D}$), and then move to fire Realm 1 detected (DS), where the human is trying to suppress the fire. Fire suppression may continue for awhile followed by fire department response. In each case, the mean realm time of interest is the mean time each case exists. Thus, for example, the mean time the fire is in Realm 1 with detection and fire department response does not include time the fire was in Realm 1 with no detection and/or manual occupant suppression.

In summary, the two table sections (a and b) are to contain the probabilities of each transition (Section a) and the mean time in a realm before transition to another realm (Section b). Each possible

he Effect of Human Actions on Fire

Tables 3-3 and 3-4 are also provided in two parts, a and b. ach table records estimated detection/action probabilities and time or the human actions affecting the fire. Two tables are provided, ne for each type of fire. Section a presents the probability of transtion from each detection/action state to other detection/action states DAS) as a function of the fire realm. Section b presents the mean exstence time of the DAS prior to transfer to another DAS as a function f fire realm. For example, the first row of Section a presents two robabilities. One is the probability of transfer from the "no detecion" to "detect-suppress" and the other is the probability of transfer rom "no detection" to "detection and Fire Department response." The orresponding entries in Section b give the mean time the system will e in the "no detection" realm before transition to "detect and suppress" r "detection and fire department response."

Note that these entries should not reflect the length of time one xpects a fire realm to exist. Instead, of concern here is the length f time the fire could develop undetected. For example, if fire detection s not expected to occur for an hour, but the fire will self extinguish fter a half hour, the model will automatically "take care of" that set f events.

The second set of seven rows corresponds to the probability of transer from "occupant fire suppression" to either "fire department response" r "occupant evacuation." Here we are interested in the probability hat the individual will notify the fire department and the mean time hat person will engage in fire suppression prior to either the fire de-

Probability of Transition From Each Fire and Human Realm Combination (represented by a row) to Other Human Realms (represented by each column)

Reference Fire # 6 of Table 2-1

		DS	DFD	E
1	$\overline{D}$	.96	.04	
2	$\overline{D}$	.92	.08	
3	$\overline{D}$	.25	.75	
4	$\overline{D}$	.05	.95	
5	$\overline{D}$	.01	.99	
6	$\overline{D}$		1.00	
7	$\overline{D}$		1.00	
1	DS		.50	.50
2	DS		"	"
3	DS		"	"
4	DS		"	"
5	DS		"	"
6	DS		"	"
7	DS		"	"

$\overline{D}$ FIRE NOT DETECTED

DS FIRE DETECTED and fire suppression initiated

DFD FIRE DETECTED and fire department responded

E Evacuation

Table 3-3a

Mean Time in Each Fire and Human Realm Combination
(represented by a row) Before Transfer to Other Human Realms
(represented by each column)

ce Fire # 6 of Table 2-1

	DS	DFD	E
$\overline{D}$	.5	.5	
$\overline{D}$	1.0	1.0	
$\overline{D}$	.5	.5	
$\overline{D}$	.5	.5	
$\overline{D}$	.5	.5	
$\overline{D}$		.25	
$\overline{D}$		.25	
DS		2.	2.
DS		2.	2.
DS		.5	.5
DS		"	"
DS		"	"
DS		"	"
DS		"	"

$\overline{D}$ FIRE NOT DETECTED

DS FIRE DETECTED and fire suppression initiated

DFD FIRE DETECTED and fire department responded

E Evacuation

Table 3-3b

Probability of Transition from Each Fire and Human Realm Combination (represented by a row) to Other Human Realms (represented by each column)

eference Fire # 9 of Table 2-1

		DS	DFD	E
1	$\overline{D}$	.96	.04	
2	$\overline{D}$	.92	.08	
3	$\overline{D}$	.25	.75	
4	$\overline{D}$	.05	.95	
5	$\overline{D}$	.01	.99	
6	$\overline{D}$		1.00	
7	$\overline{D}$		1.00	
1	DS		.50	.50
2	DS		"	"
3	DS		"	"
4	DS		"	"
5	DS		"	"
6	DS		"	"
7	DS		"	"

D FIRE NOT DETECTED

DS FIRE DETECTED and fire suppression initiated

DFD FIRE DETECTED and fire department responded

E Evacuation

Mean Time in Each Fire and Human Realm Combination
(represented by a row) Before Transfer to Other Human Realms
(represented by each column)

Reference Fire # 9 of Table 2-1

		DS	DFD	E
1	$\bar{D}$	8.	10.	
2	$\bar{D}$	4.	4.	
3	$\bar{D}$	.5	.5	
4	$\bar{D}$	.5	.5	
5	$\bar{D}$	.5	.5	
6	$\bar{D}$		.25	
7	$\bar{D}$		.25	
1	DS		2.	2.
2	DS		2.	2.
3	DS		.5	.5
4	DS		.5	.5
5	DS		.5	.5
6	DS		.5	.5
7	DS		.5	.5

D FIRE NOT DETECTED

DS FIRE DETECTED and fire suppression initiated

DFD FIRE DETECTED and fire department responded

E Evacuation

Table 3-4b

Human Response Parameters

This section presents tables for recording estimates of movement parameters for individuals not affecting the fire. Table 3-5 gives the four types of human mobility organized into two categories. Tables 3-6 and 3-7 provide a means for recording the probability of transition from one location to another and the mean time in each location prior to transition. Table 3-6 is used with human mobility Category 1 (people capable of self-preservation) for each of the seven fire realms. Table 3-7 is associated with human mobility category 2.

The first part of each table presents the probability of transition from the location indicated by the row to the location indicated by a column. The second part of the table presents mean time an individual is in the location indicated by the row prior to transitioning to the location indicated by a column. In actual use Tables 3-6 and 3-7 each consists of seven pages where each page would be associated with a particular human mobility category and a fire realm. Thus, Table 3-6 consists of the seven pages where each of the seven pages would correspond to one fire realm. For the sake of example only the first page of each table (corresponding to Realm 1) is shown here.

ategory 1 People Capable of Self Preservation

- Awake, non-disabled children of school age and adults

ategory 2 People Who Are Nonambulatory, Infantile, Senile, or Otherwise Incapable of Self Preservation

- Sleeping, non-disabled children of school age and adults
- Physically or mentally impaired (including drugged) children of school age and adults
- Elderly

Table 3-5 Mobility Categories of Individuals

Response Times and Transition

Probabilities for Humans Not Affecting Fire

Mobility Category 1

Fire Realm 1

Probability Of Transition From Location (indicated by row)
To Another Location (indicated by column)

Relative Location of Individual	1	2	3	4	5	6
1. Room of fire origin	.919	.01	.02	.001		.05
2. Floor of fire origin	.90	.04	.02	.02	.01	.01
3. Exit	.90			.02	.04	.04
4. Floor beyond	.06	.04	.10	.60	.10	.10
5. Other dwelling	.001				.999	
6. Outside dwelling	.001					.999

Mean Time* Individual Is in Location (indicated by row)
Before Transitioning to Another Location
(indicated by column)

Relative Location of Individual	1	2	3	4	5	6
1. Room of fire origin		4.	4.			
2. Floor of fire origin	10.		10.	10.	10.	10.
3. Exit	10.	10.		10.	10.	10.
4. Floor Beyond	15.	15.	15.		15.	15.
5. Other dwelling	5.					
5. Outside dwelling	5.					

*Time in minutes

Table 5-7

Response Times and Transition

Probabilities for Humans Not Affecting Fire

Mobility Category 2

Fire Realm 1

Probability Of Transition From Location (indicated by row)
To Another Location (indicated by column)

Relative Location of Individual	1	2	3	4	5	6
1. Room of fire origin	.95	.02	.01	.01	.005	.005
2. Floor of fire origin	.05	.93	.005	.005	.005	.005
3. Exit	.01		.96	.01	.01	.01
4. Floor beyond				.9998	.0001	.0001
5. Other dwelling					1.000	
6. Outside dwelling	.01					.99

Mean Time Individual Is in Location (indicated by row)
Before Transitioning to Another Location
(indicated by column)

Relative Location of Individual	1	2	3	4	5	6
1. Room of fire origin		5.	5.	5.	5.	5.
2. Floor of fire origin	15.		15.	15.	15.	15.
3. Exit	15.					
4. Floor beyond					10.	10.
5. Other dwelling						
6. Outside dwelling	10.					

A Test of the BFM

A digital computer simulation implementing the fire development and human response models has been developed. In order to test the simulation, the fire dynamics and human response parameter values estimated for the hypothetical dwelling and individuals given in the previous section were input to the computer simulation. Initial fire conditions were set at Realm 1 with no detection ($\bar{D}$) of fire. One thousand fire developments were produced - each according to the probabilities indicated.

In addition, certain probabilities were modified and the simulation repeated to reveal the effect of the modified probabilities on fire development. This is called sensitivity analysis. Such analysis permits a determination of the relationship between a fire development parameter (and in turn a building parameter) and the properties of fire development.

Simulations were run for several types of fires and human mobility categories. Results of the simulations for fire type 6 (source of heat: kitchen stove; location of ignition: kitchen; first material ignited: fabric; Table 2-1) and human mobility category 1 (People Capable of Self Preservation, Table 3-5) are given in Figures 3-1 through 3-3.

Figure 3-1 provides the probability of being in each realm for each one minute time increment. Quarter minute intervals were used in the simulation with results averaged over a minute for the plots. Note that after one minute 11.4 percent of the fires remain in the Realm 1 category, the remaining fires have either self-extinguished or transferred to other realms. After 15 minutes, the probability of a fire type 6 being in Realm 1 is zero. Likewise the probability of being in Realm 2

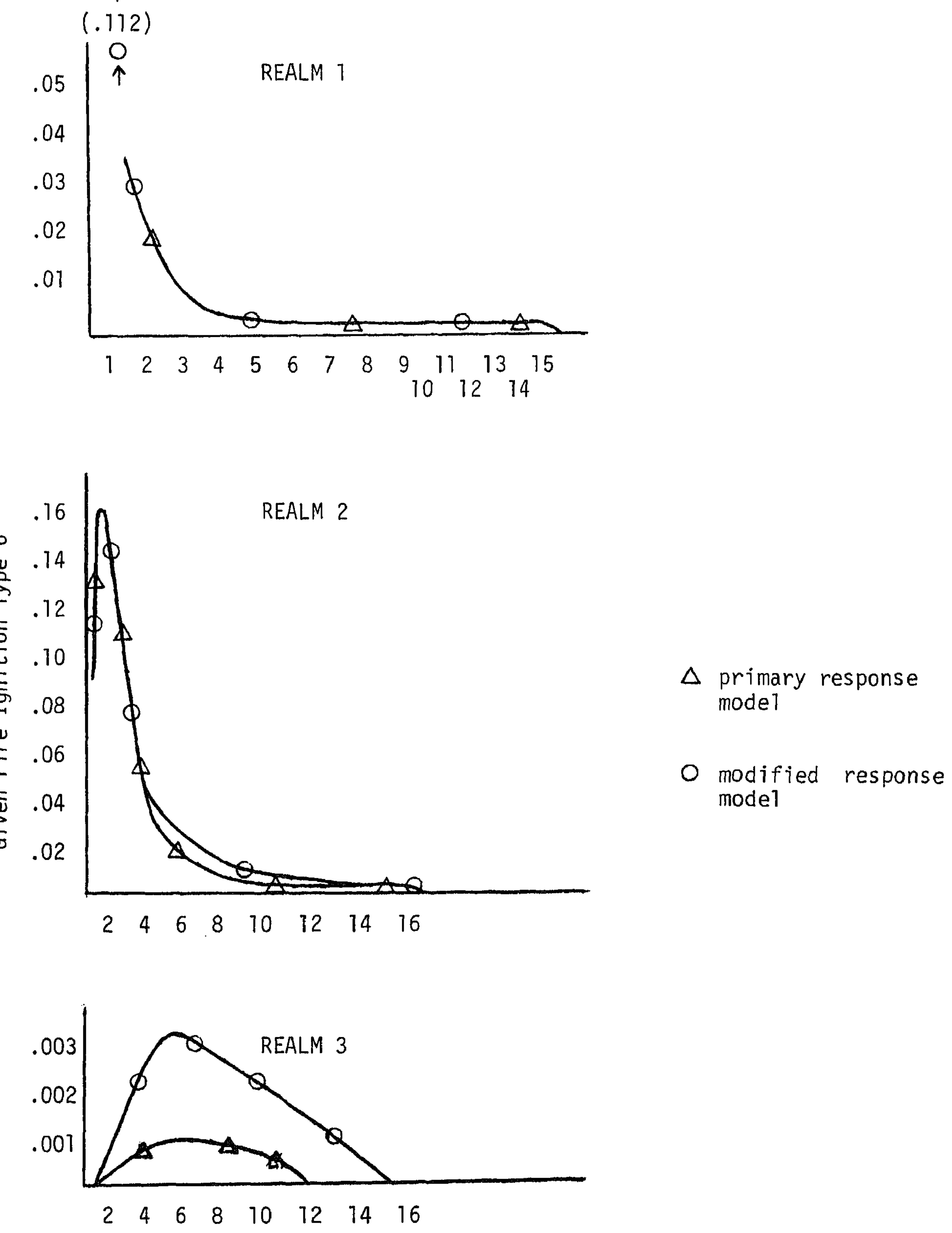


Figure 3-1a Realm/Time Distributions for

Initial Condition 1st Mat, $\bar{D}$

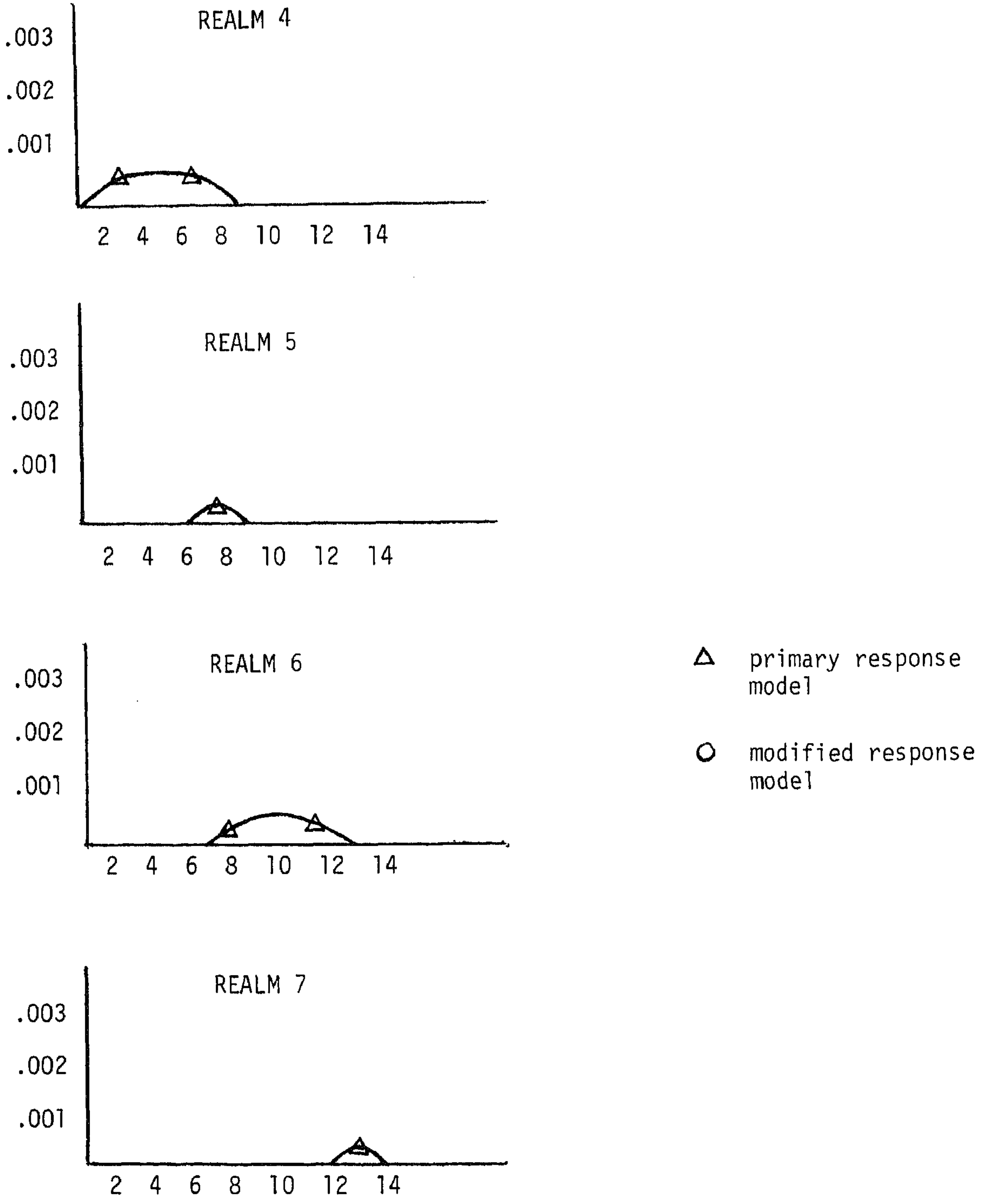
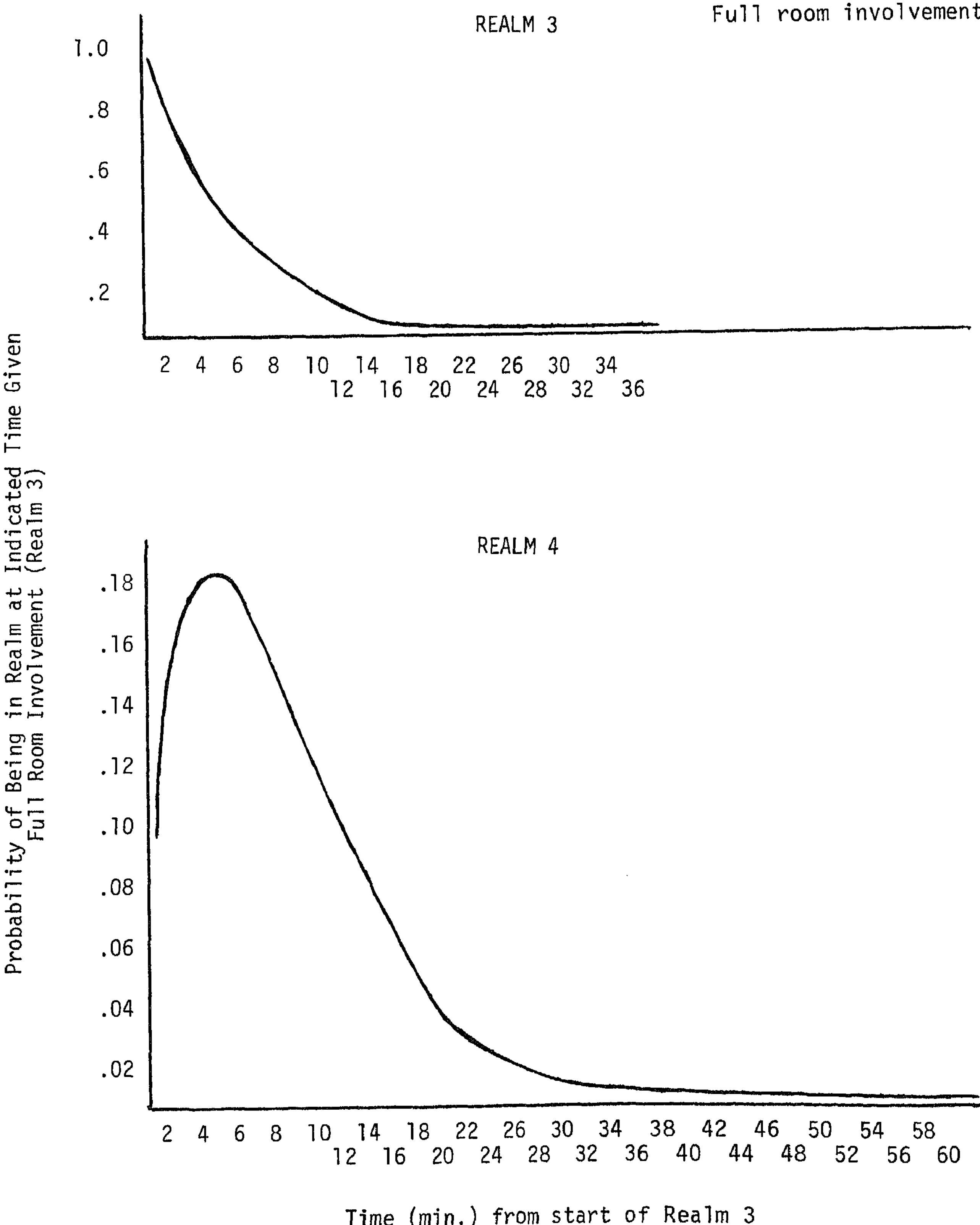


Figure 3-1a (continued)

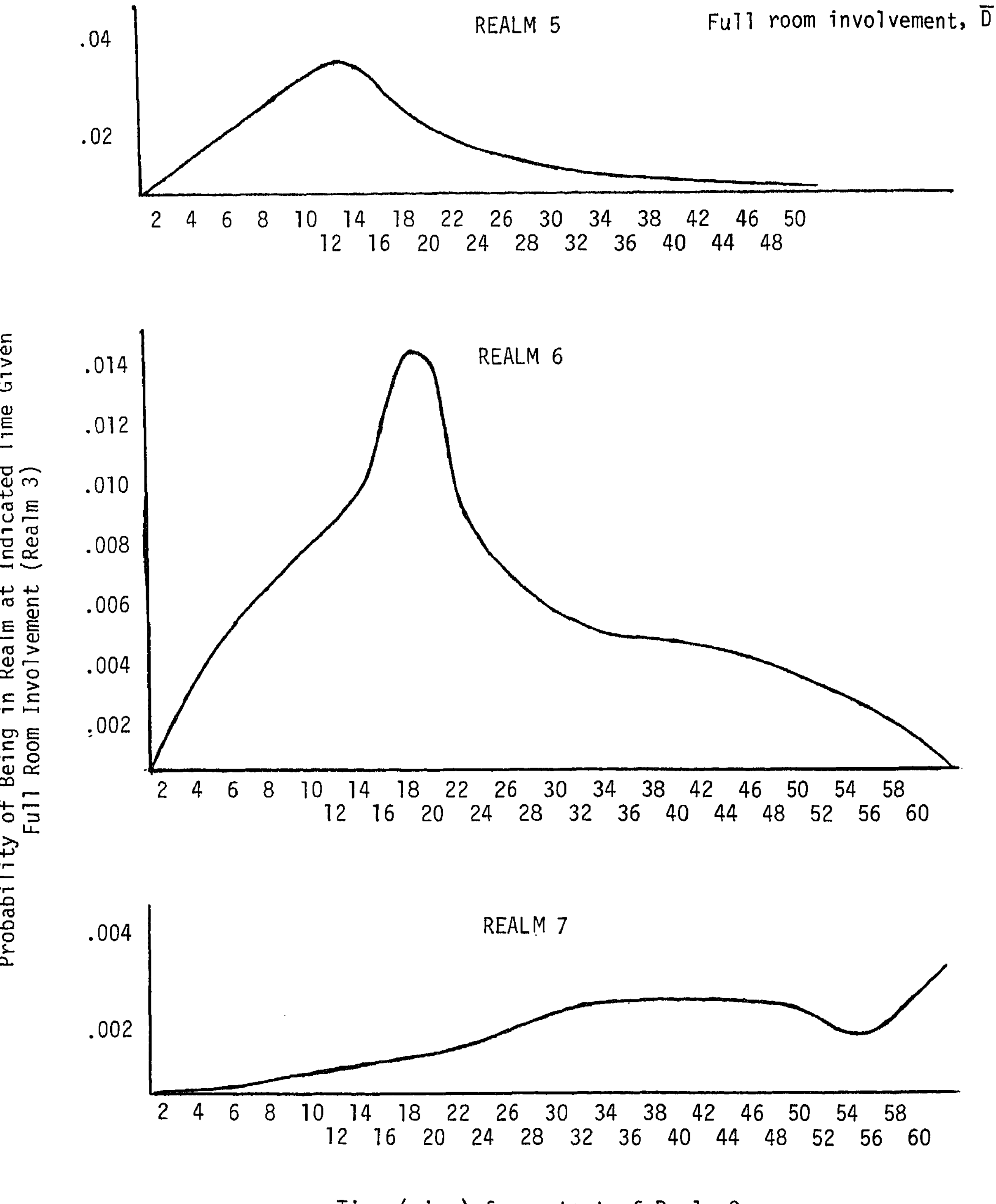
Initial Condition

Full room involvement



Initial Condition

Full room involvement, $\overline{D}$



ter 16 minutes is essentially zero. This is apparently due to sup-
ession activity and an artifact of the simulation. (Note that the ponse of the primary model which corresponds to the data of Figure is shown by an "Δ". An "O" is used to show the response of modid data to be explained subsequently.)

The simulation reveals that a probability of .00025 to .001 of being Realm 3 over the time interval 1 to 5 minutes. Probability limits s than .00025 are indicated as zero because the simulation used 0 runs with 4 intervals averaged over 1 minute. The .00025 it provides a truncation of the distributions at 13 minutes for lm 1, 14 minutes for Realm 2, and 12 minutes for Realm 3. If 10,000 s were used, probabilities of .000025 could be indicated.

A practical way to extend the resolution of the simulation and per- investigation of the response of the remaining realms, is to use a -phase simulation. First, fires are simulated starting at fire inition. From this simulation, probability distributions are developed well as other fire development properties. One property of interest the probability (P_3) of reaching Realm 3. Secondly fires starting Realm 3 are simulated. Fire distributions as shown in ure 3-1 and 3-2 resulting from such a fire simulation must be weighted P_3.

The effect of the modified data, corresponding to a change in a lding/human response parameter, is illustrated by the modified rense shown in Figure 3-1a. Probabilities for the primary and modified el situation "Realm 1, DS" (fire Realm 1, detection and occupant sup-

	Transfer to Realm 0	Transfer to Realm 2
Primary Model	.99	.01
Modified Model	.90	.10

An increase in the probability of transfer to Realm 2 greatly increases the probability that the fire will be in Realm 3. While the results presented are for a hypothetical dwelling and assumed realm time distributions (geometric distributions are assumed) are used, these results indicate how sensitivity analysis can be used to reveal the impact of building parameters and human responses.

Human response simulation provides the probability of the individual being in a specific location relative to the fire as a function of time since fire initiation. Figure 3-2 shows these probabilities. Of specific interest is the probability of the individual being in a location at a time when products of combustion are possibly injurious.

Figure 3-3 illustrates summary data for the fire development by providing the average time of fire as a function of fire detection/ suppression activity.

The numerical results given here are offered to illustrate the type of data produced by the model. Data for all types of fires are not presented because of the volume and the hypothetical nature of the represented dwelling. The results were not just illustrative of the research program, however. Analysis of the data showed that:

- Realm times may be different depending on the next realm (a property affecting model design).

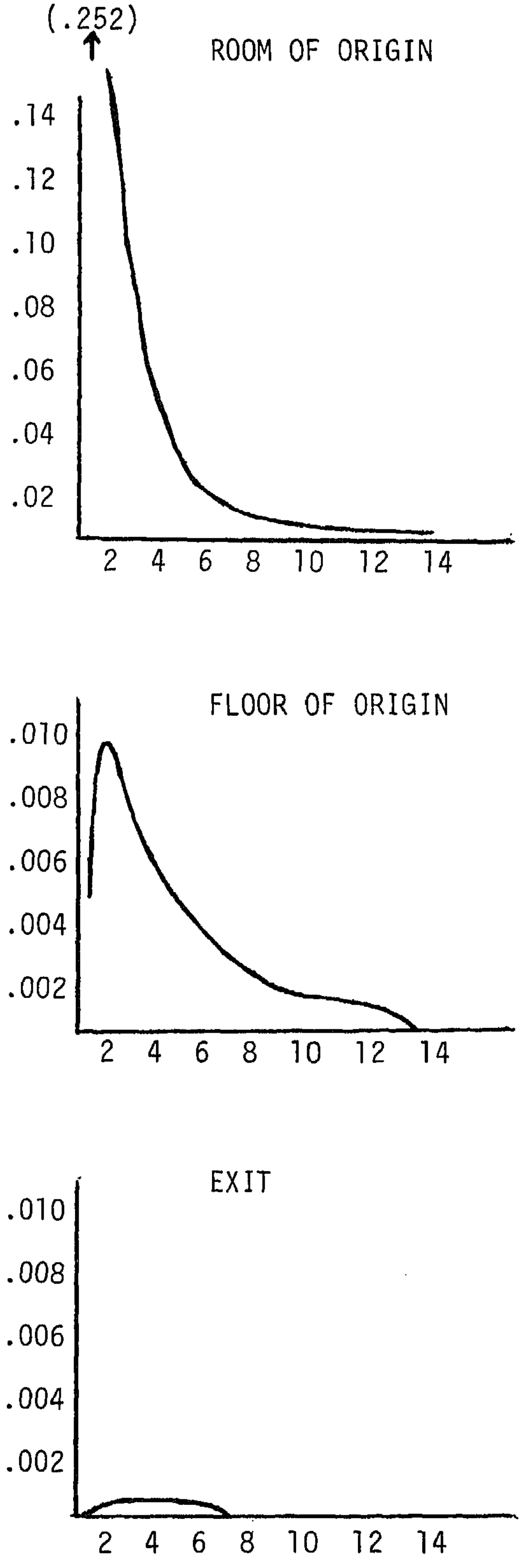
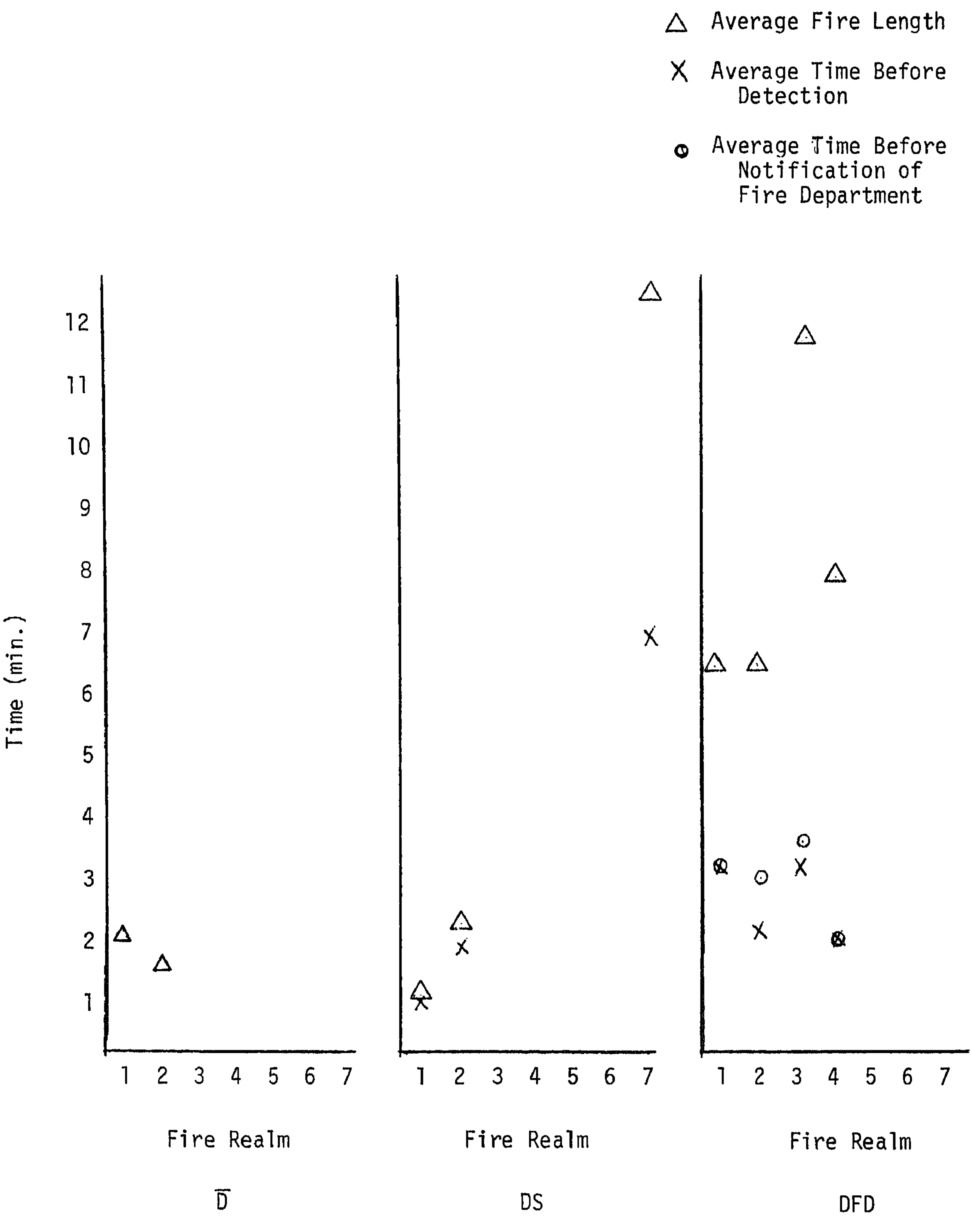


Figure 3-2 Location/Time Distribution for Hypothetical Individual Category 1


Average Fire Length
Average Time Before Detection
Average Time Before Notification of Fire Department
Time (min.)
12
11
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7
Fire Realm
$\overline{D}$
DS
DFD

- There is a need to explicitly represent the sequence of events resulting in the fire department arrival.
- There is a need for an investigation of the actual realm distributions.

Model Test: Effect on P_{FSOC} of Kitchen Wall Material

The digital computer program used to implement fire development and human response has been expanded to include building parameter conversion logic, products of combustion development, and firesafety objective competent Logic.

The program was developed by a modular method which enabled each section to be developed independently. A flow chart of two of the sections, POC spread and FSOC logic, is shown in Figure 3-4. The modular approach has an additional benefit. When new data or new analytical methods are developed, they may be included by changing only the appropriate modules and leaving the rest of the program untouched.

As a means of demonstrating the feasibility of the approach and also to test the expanded program, the BFM has been applied to a kitchen fire in a single-family dwelling. Various parameters, such as the effect of fire on POC development, had to be estimated because of lack of specific analytic data. These parameters were added to the program in a manner which allows easy modification in the future. The expanded digital program, variables used, and results are explained in the following paragraphs.

The Parameter Conversion Logic section of the BFM enables various fire parameters to be converted into a form useable to a digital computer program. Parameters are described in terms of changes to the original transition probabilities and mean times described in Tables 3-1 and 3-2. Using professional judgement, available data, and fire tests, it is possible to determine which transition probability(s) and mean time(s) will be af-

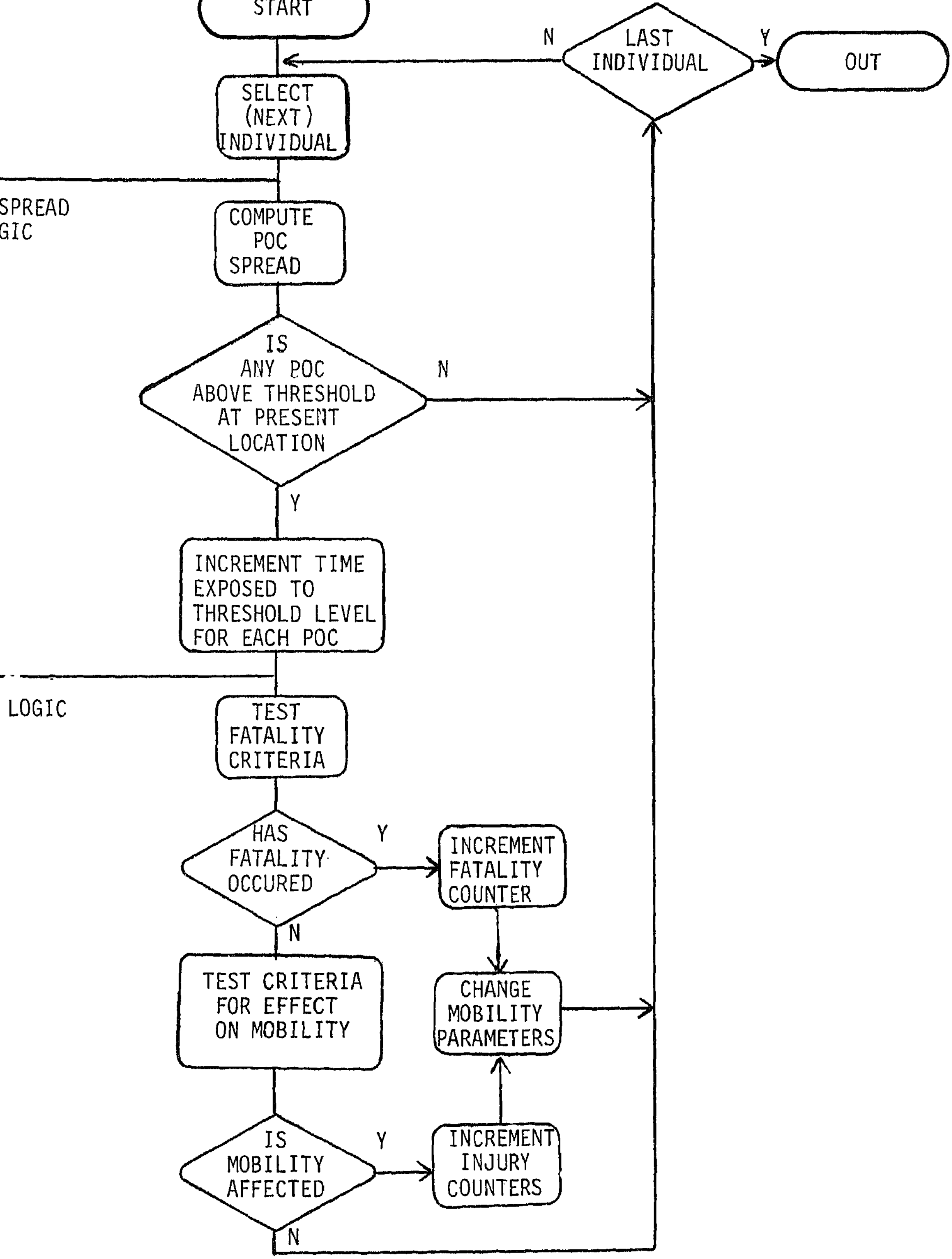


Figure 3-4. POC and FSOC Subroutines

form a data handbook. Parameter values presently in the handbook are those developed for the test application of a kitchen fire. The building characteristics considered for this fire are:

- all walls constructed with gypsum wall board (except for cabinets)
- one wall paneled (180 flame spread rating) and the other walls gypsum
- all walls paneled (180 flame spread rating)

Each parameter set has been evaluated to determine its effect on the probability of transitioning from Realm 2 (second material involved) with no human intervention to Realm 3 (full room involvement). A new mean time (in minutes) of remaining in that realm was also determined. These new values are shown in the figure below:

	Parameter Set		
	1	2	3
new transition probability	.05	.10	.11
new mean time	8	6	5.5

These new values are tabulated and punched on computer cards. The digital computer program changes the fire transition table and mean time table to reflect these changes. The original values are in Tables 3-1 and 3-2.

One of the requirements of the fire transition table is that the sum of the probabilities in each realm transition row must add up to 1.0. To accomplish this the changed element of the row is set to the input

and the rest of the elements are multiplied by weighted correc-
value which forces the total of the row to be 1.0.

For example, in case 2 the new transition from Realm 2 to 3 is .10.
revious Realm 2 row is shown below:

	0	1	2	3	4	5	6	7
$\bar{D}$	.70	.25	X	.05	0.0	0.0	0.0	0.0

lement under column 3 is changed to .10, and all other elements
ultiplied by (1.0 - .10)/(1.0 - .05) = .9474. This gives the new
2 row shown below, which satisfies the original requirement, that
um of the probabilities equals 1.0.

	0	1	2	3	4	5	6	7
$\bar{D}$	.66	.24	X	.10	0.0	0.0	0.0	0.0

Products of Combustion Model

This section of the BFM computes the severity of the POC according to the present fire realm. Three different levels of severity are distinguished. Level 1 is a slight hazard, such as low temperature and low concentrations of carbon monoxide (CO), level 2 is a medium hazard, and level 3 is a severe hazard. A table relating each POC used in this example (CO and temperature) to the associated hazard of each fire realm is shown in Table 3-8.

The POC model also tabulates the total amount of time an individual is exposed to each level of CO and temperature hazard. To do this, it is necessary to know which fire realms can potentially effect each location (Table 3-9). For example, if a person is outside the dwelling, that person will not be affected by the fire. However, if the person is on the floor of fire origin, that individual will be affected when the fire reaches the second room. When any effect of the fire occurs, the total time of exposure to the products of combustion increases. These times are used in the FSOC logic portion of the BFM to determine the extent of human injury.

Fire Realm	Products of Combustion	
	Carbon Monoxide	Temperature
irst Material Involved	1*	1
econd Material Involved	2	1
oom of Origin Fully Involved	2	2
econd Room Involved	3	2
loor of Origin Fully Involved	3	2
loor Beyond Involved	3	3
welling Fully Involved	3	3

1 = slight hazard

2 = medium hazard

3 = severe hazard

HUMAN LOCATION	FIRE REALM
Room of fire origin	First material involved
	Second material involved
	Room of origin fully involved
Floor of fire origin	Second room involved
	Floor of origin fully involved
Exit	Full floor
	Floor beyond
Floor beyond	Floor beyond involved
	Dwelling fully involved
Other dwelling	None
Outside dwelling	None

Logic Model

The effect of exposure to different levels of products of com-
ion varies with the total time exposed. The FSOC which is being ied in this test case is the probability of a fatality. A fatality occur at each of the three levels of hazard for both CO and temper- e, depending on the total time exposed. Exposure to temperature rd level 3 for .30 min. can cause a fatality, as well as exposure evel 2 for 10 min., and level 1 for 1 hour. The same is true for A complete table is shown in Table 3-10.

There are two possible mobility impairments other than a fatality. e are slight and severe impairment, which correspond to slight and ous injury. The serious injury is tabulated as an injury even though ne future it could lead to edema and death. The different effect on le is caused by the different exposure times to each level of hazard le 3-10). These effects on mobility lead to changes in the probabil- of the people staying in their present location. The new probabili- are:

slight impairment = .25 probability of staying

severe impairment = .50 probability of staying

fatality = 1.00 probability of staying

CARBON MONOXIDE

Hazard Level \ Mobility Impairment	Slight	Severe	Fatal
1	10.0 min.	20.0	30.0
2	.60	2.0	5.0
3	.30*	0.30	0.30

TEMPERATURE

Hazard Level \ Mobility Impairment	Slight	Severe	Fatal
1	10.0 min	30.0	60.0
2	2.0	5.0	10.0
3	0.30	0.30	0.30

*In the model 0.30 is the smallest time interval. It is as close to instantaneous as is possible to input to the model.

lts of the Test

The purpose of the model is to evaluate the effectiveness of ges in building parameters with respect to fire safety. In this ple, we have altered a particular building characteristic, kitchen rior wall finishes. The fact that the model output shows differ- s in fire development consistent with the changed parameters in- tes that the model developed in this report produces at least logical- onsistent results.

When the fire development was simulated using the new probabilities mean times caused by the changes in wall finish described previously, ral observations were made: First, the fire developed more rapidly had a greater likelihood of being severe (Figure 3-5). Second, the ability of injury increased as the finish materials became less flame rdant. Finally, the probability of a fatality remained the same le 3-11), at least for the computer runs conducted.

With an increased flame spread rating, it would be expected that s would be more likely to develop rapidly and with greater severity. rapid development of this new fire explains the increase in the prob- ity of injury. As the fire advances, the occupants are not able to t quickly enough and will be injured in the process. However, the that the likelihood of death is not increased by the increased fire ad rates indicates that the changes in mean times and transition abilities used in the example were not significant enough to prevent occupants in the room of origin from escaping death for these test

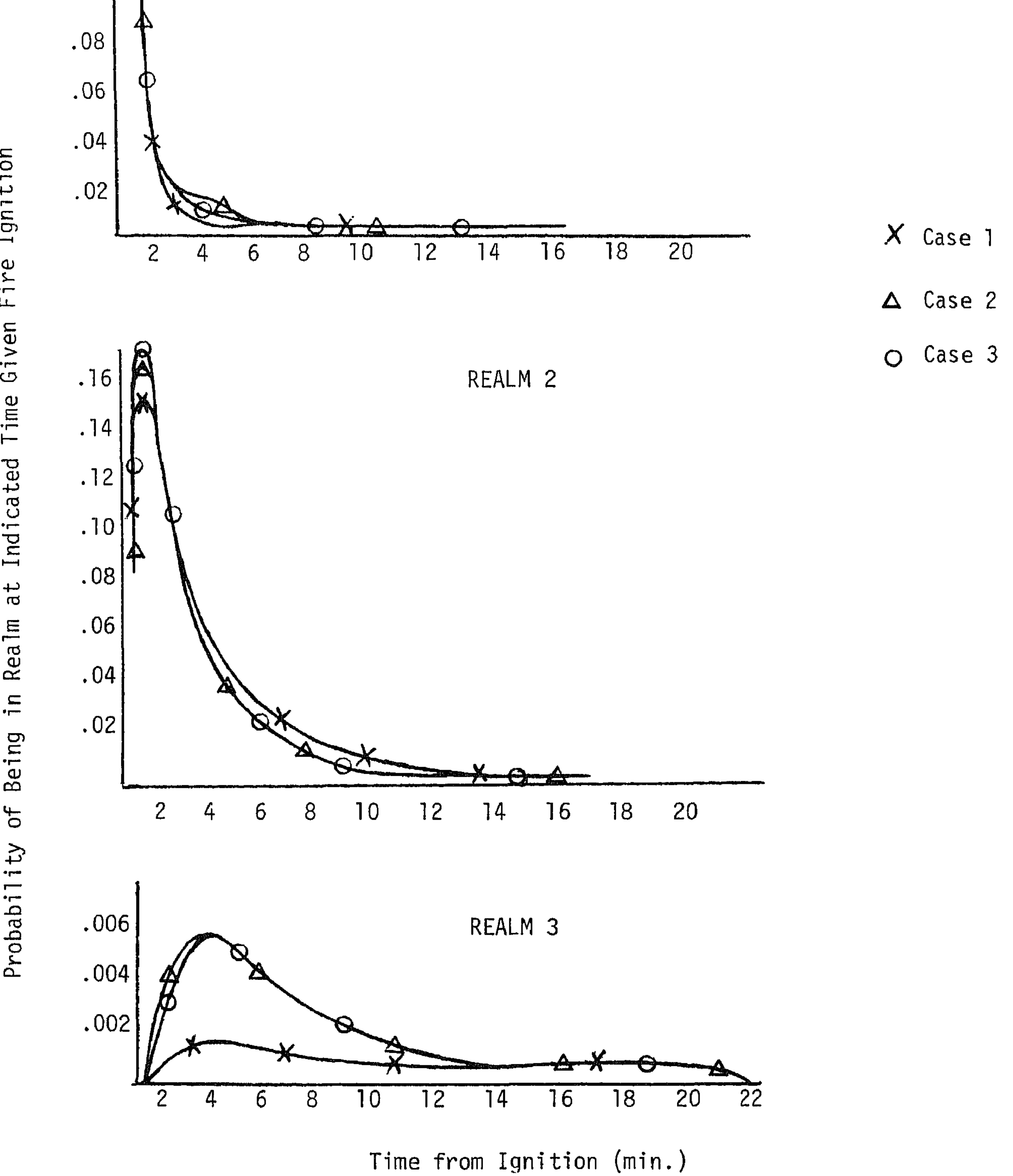
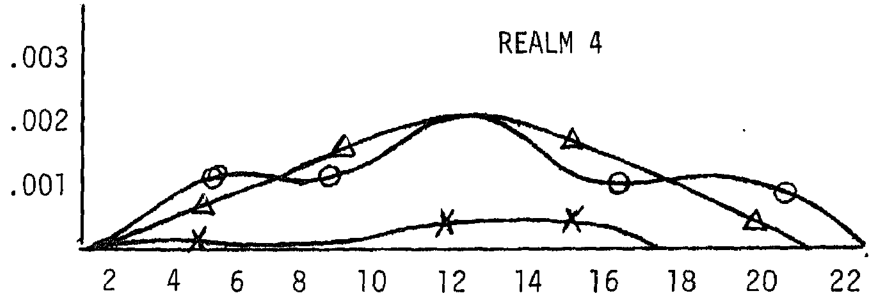


Figure 3-5 Realm/Time Distributions for Each Type of Kitchen Wall Covering



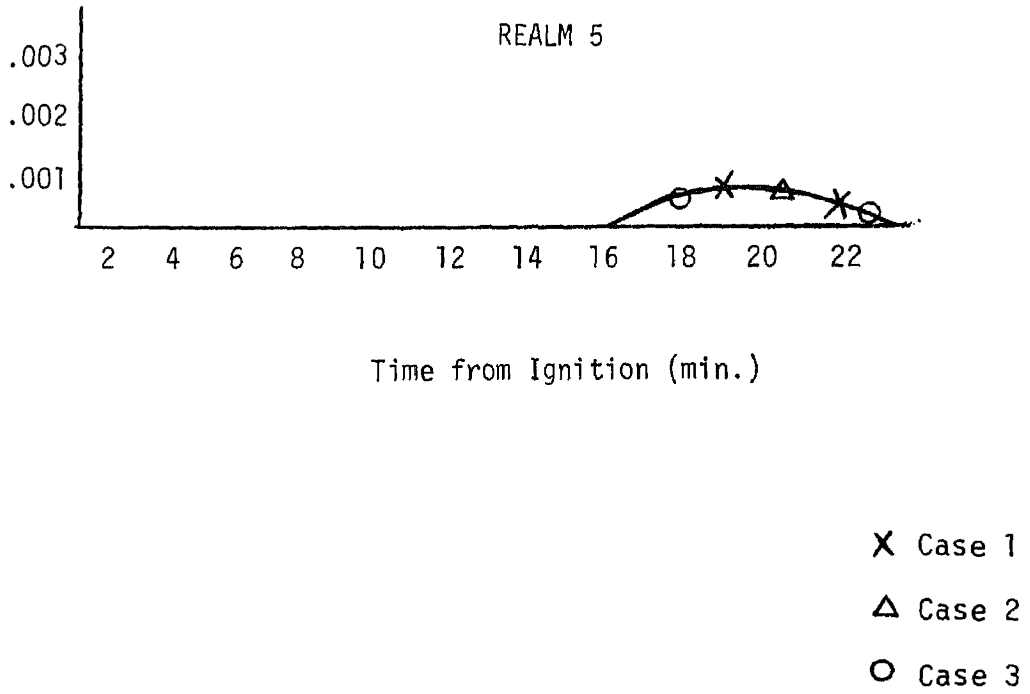


Figure 3-5 (continued)

Type of Injury / Case*	Slight	Serious	Fatal	Total
1	.090	.160	.023	.273
2	.099	.160	.023	.282
3	.100	.162	.023	.285

*Cases are as described on page 64

Table 3-11 Probability of Injury and Fatality for Each Type of Kitchen Wall Finish

CHAPTER IV

SUMMARY OF RESULTS AND PLANNED MODEL REFINEMENTS

ary of Results

The Building Firesafety Model (BFM) is a tool that simulates the
nics and interaction of the major fire factors from ignition to
guishment. Fire factors are categorized in the BFM components
ollows:

- Parameter Conversion Logic (PCL)
- Fire Development Model (FDM)
- Human Response Model (HRM)
- Products of Combustion Model (POCM)
- Firesafety Objective Component Logic (FSOCL)

Models have been constructed, programmed for a digital computer,
ested. In some cases portions of the BFM were constructed in a
ified manner to permit testing of the modeling concept. PCL,
converts fire development parameters from building parameters, was
sed and fire development parameters (realm times and transition
bilities) estimated directly. Similarly, simplified POC and FSOCL
ions were used. The HRM included only the movement of people in
situations, and the effect of detection and suppression activity
re spread.

Data for model construction and test are based on published liter-
and on the judgement of professional fire protection engineers. With
data, fire in kitchens with different wall finishes was compared.

FSOC probabilities for the cases studied, and established the feasibility of the approach used for the BFM.

nned Model Refinements

Future work on the BFM will incorporate additional features that e purposely omitted in the initial model so that this model may be ended for application to additional types of dwellings and to de-op general application techniques for the user. Additional features be incorporated are:

1. Generation and propagation of smoke and other products of combustion
2. Refinement of the HRM to include other affects of human actions on fire development
3. Effects of structural and barrier failure on fire development
4. Effects of POC on an individual's mobility
5. Extension of the FSOC criteria to incorporate data on injury, fatality, structural damage, and mission

The BFM will be modified to represent fire development in other sses of housing: multifamily, care-type, and mobile homes. Ex-sion of the model to the multifamily case will involve consideration structural integrity, compartmentation, sprinkler protection, detectors. Models for care-type housing will include consideration sprinklers, detectors, compartmentation, and special classes of human avior. Mobile homes will require more changes in the models than the other cases, since this is a more complex fire problem. Con-ction practices unique to mobile homes require special consideration eometry, ventilation, and exits, etc.

be in a form that is useful to builders, designers, code writers and approval authorities. Quantified parameters (e.g., room size, fuel load, flame spread rates) will be the inputs to the BFM. These inputs will be converted via the PCL to fire development parameters. This conversion is accomplished by altering the appropriate FDM transition probabilities.

According to the present plan, the output of the BFM will take two forms. One form consists of a computer printout revealing P_{FSOC} for a new or unique building design. The other form is an application guide for more conventional designs. The application guide will consist of graphs and tables showing the P_{FSOC} as a function of building parameter

Since the BFM must always represent current knowledge of fire and its effects, its design must allow for constant updating. To accomplish this the BFM and its computer program have been designed in modular form.

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APPENDIX A

MODELING OF THE TIME-VARYING TRANSITION PROBABILITIES OF FIRE REALMS

Introduction

One way to model fire spread is to define fire states (realms) and represent fire spread by probabilities of transition from one realm to another. This approach is based on the fact that flame properties are largely determined by the fuel and oxygen immediately available, and are not greatly influenced by previous events such as the type of ignition. As a result, a fire realm can be defined by an existing condition, not by a sequence of conditions. This property, whereby the process is defined by the present state (realm) and not by previous realms, permits modeling of the fire spread process by fixed probabilities of transition from one realm to another. A feature of this approach is that the process, as modeled, is a Markov process for which a great amount of mathematical theory is available.

Another property of fires which must be modeled is the fact that the length of time a fire burns in a given realm affects future fire spread. For example, the probability of a wall burn-through from a room fire increases with fire severity. This property may appear to negate fire spread modeling with a Markov process since the transition probabilities may vary with realm severity. However, each realm can be subdivided into sub-realms, as necessary, where each sub-realm represents fixed realm time, and fixed transition probabilities can be associated with each sub-realm. Furthermore, the number of sub-realms

roach

A state is considered absorbing if a process will never leave once it enters. Consider a Markov process with one transient state one absorbing state as shown in Figure A-1.

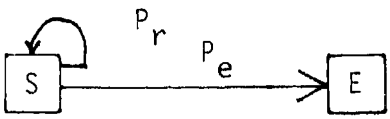


Figure A-1 Simple Markov Process

Let the outcome event be the entrance into the absorbing state Then the probability $P_r(n)$ of entering E in exactly n time ervals, assuming each transition takes up one time interval, is e probability of remaining in state S for n-1 time intervals which curs with probability P_r^{n-1}, times the probability of transition to e absorbing state on the next interval which occurs with probability Thus,

$$P_r(n) = P_r^{n-1} \; P_e$$

ere

$$P_r + P_e = 1 \qquad (1)$$

A more general Markov process may be constructed by defining each ate S_i to be the event that the outcome takes at least i units of ne. One system for such a process is shown in Figure A-2.

This model is more powerful than the previous one in that the tcome achieved by entering an absorbing state is accomplished by

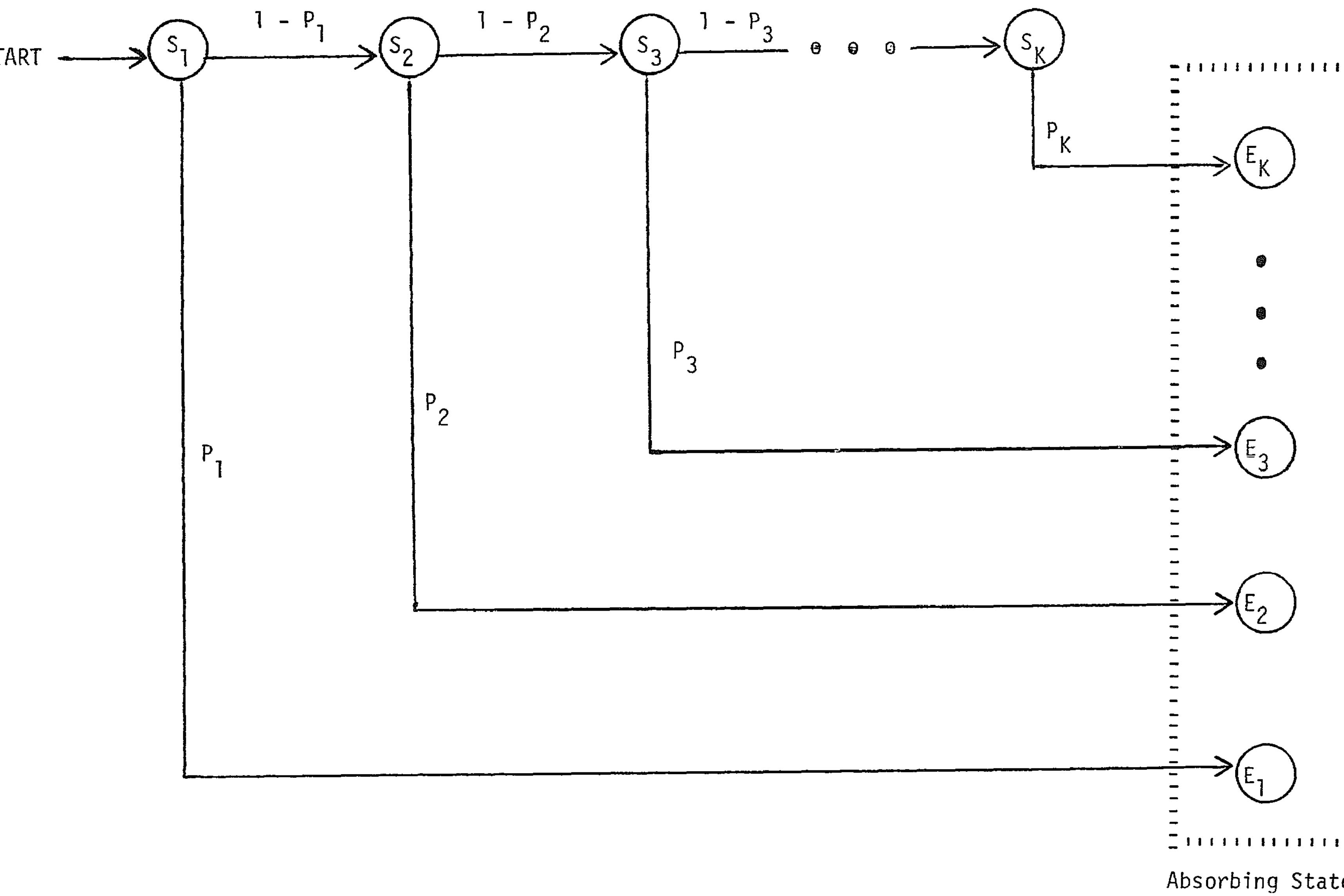


Figure A-2 A General Time Delay Process

This process model can be used to represent the existence of
ealm with an arbitrary time distribution. The realm "existence"
rts when the process moves to the sub-realm (state) S_1. It
minates when the process moves to one of the absorbing states
, E_2, . . . E_k). If the process terminates in exactly one interval,
exists via state E_1. Likewise if the process terminates in exactly
ntervals, it exits via state E_i. Since the exit state is a unique
ction of the number of intervals, transition probabilities from
realm can be assigned to each absorbing state E_i. Thus fixed
nsition probabilities which reflect the desired function of time
be assigned to each absorbing state E_i. This allows different
nsition probabilities, which can be assigned without restriction,
be associated with each process time interval.

In the above discussion, states E_i are treated as absorbing
h respect to the other sub-realm states S_i. This is to facilitate
culations; however, states E_i are actually entry points to the
sequent realms.

The probability distribution for entering any absorbing state
for the general Markov process may be obtained by constructing
transition matrix (Z) as shown in Figure A-3. In the transition
rix, all absorbing states are combined into state (E) to facili-
e calculation of transition probabilities for specified time
tributions. Each matrix entry a_{ij} denotes the probability of
cess transfer from the state assigned to row i to the state

$$
\begin{array}{c|c|ccccc}
 & E & S_1 & S_2 & S_3 & \cdots & S_K \\
\hline
E & 1 & 0 & 0 & 0 & 0 & 0 \quad \cdots \\
\hline
S_1 & P_1 & 0 & 1-P_1 & 0 & 0 & 0 \\
S_2 & P_2 & 0 & 0 & 1-P_2 & 0 & 0 \\
S_3 & P_3 & 0 & 0 & 0 & 1-P_3 & \\
\vdots & & & & & & 1-P_{K-1} \\
S_K & P_K & & & & & \\
 & & \vdots & & & &
\end{array}
=
\left[\begin{array}{c|c}
1 & 0 \\
\hline
R & Q
\end{array}\right]
$$

Let Π_o be a column vector where element b_i denotes the initial obability of being in the state assigned to row i. Since the ocess is always started in state S_1, it follows that Π_o is

$$\Pi_o = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{bmatrix}$$

Let Π_n be the probability vector of being in each state in $\underline{n}$ me intervals. Then it follows from the definitions of Z and Π_o that

$$\Pi_n = Z^{T(n-1)}\Pi_o = \begin{bmatrix} 1 & R^T \left[\sum_{i=1}^{n} (Q^T)^i\right] \\ 0 & (Q^T)^n \end{bmatrix} X \begin{bmatrix} 0 \\ 1 \\ 0 \\ \cdot \\ \cdot \\ 0 \end{bmatrix} \qquad (2)$$

ere Z^T, R^T, and Q^T are transpose matrices.

Thus element 1 of Π_n denotes the cumulative probability F(n) entering any absorbing state. Thus it follows that the probability n) of entering an absorbing state in exactly $\underline{n}$ time intervals is:

$$f(n) = F(n) - F(n-1) - \text{element 1 of } (\Pi_o - \Pi_{n-1})$$

$$= \text{element 1 of } \left[R^T (\sum_{i=1}^{n} Q^{Ti}) - R^T(\sum^{n-1} Q^{Ti})\right]$$

$$= \text{element 1 of } \left[R^T \quad Q^{nT}\right] = \text{element 1 of } (Q^n R)$$

$$= P_n (1-P_{n-1}))1-P_{n-2}) \ldots (1-P_1) = P_n \prod_{i=1}^{n-1} (1-P_i)$$

In applications where the desired time distribution is known, it can be sampled at equal intervals to yield $f(i)$, $i = 1, \ldots, n$. Then the transition probabilities (P_k) are calculated from

$$
\begin{aligned}
P_1 &= f(1) \\
P_2 &= f(2)/(1 - P_i) \\
&\;\;\vdots \\
P_k &= \left(f(k) \Big/ \prod_{i=1}^{k-1} (1-P_i) \right) = \frac{f(k)}{f(k-1)} \left(\frac{P_{k-1}}{1-P_{k-1}} \right)
\end{aligned}
\qquad (3)
$$

The corresponding process shown in Figure A-2 has the probability distribution determined by the $f(i)$.

The various $f(i)$ are determined by sampling a given time distribution. As the width of the sampling interval (and thus the unit of time in the Markov process) is made smaller, the set of $\{f(i): i = 1, \ldots, n\}$ will approximate the distribution more accurately.

Example: Model for a realm with normally distributed time

As an example, consider a realm with an existence time which is normally distributed (mean of 3.4 and a variance of 1) as shown in Table A-1. A sampling time interval of 0.68 is used. The probabilities f(n) are the probabilities the realm will exist for exactly n intervals. The transition probabilities P_i are obtained using Equation 3. The resulting process is shown in Figure A-4.

TIME DELAY	$\underline{n}$	f(n)	P_n
$(-\infty, 0.68)$	1	0.0033	0.0033
(0.68, 1.36)	2	0.0174	0.0175
(1.36, 2.04)	3	0.0662	0.0676
(2.04, 2.72)	4	0.1614	0.1768
(2.72, 3.40)	5	0.2517	0.3348
(3.40, 4.08)	6	0.2517	0.5034
(4.08, 4.76)	7	0.1614	0.6500
(4.76, 5.44)	8	0.0662	0.7618
(5.44, 6.12)	9	0.0174	0.8406
$(6.12, \infty)$	10	0.0033	1.0000

Mean = 3.4

Variance = 1.0

Sampling time = 0.68

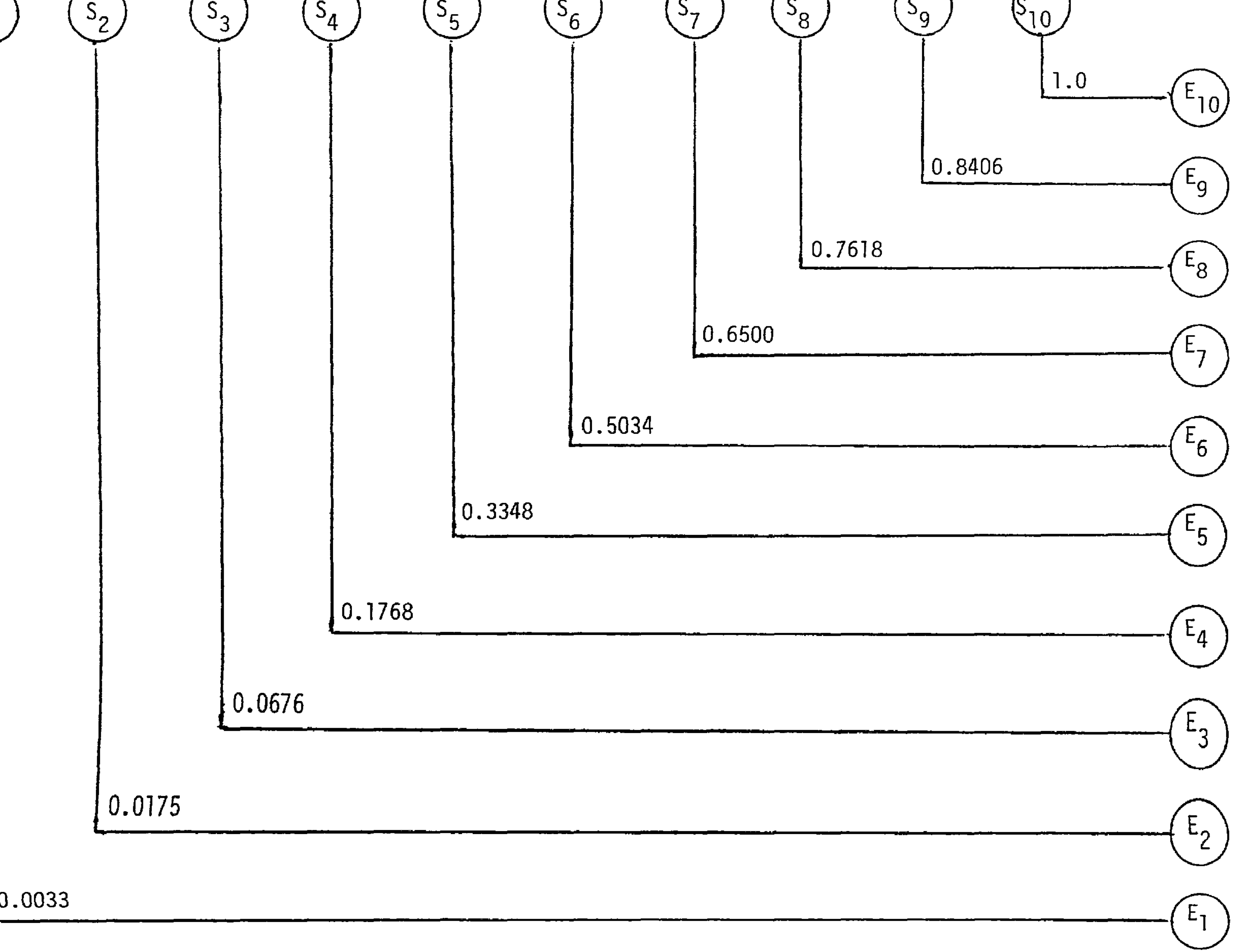
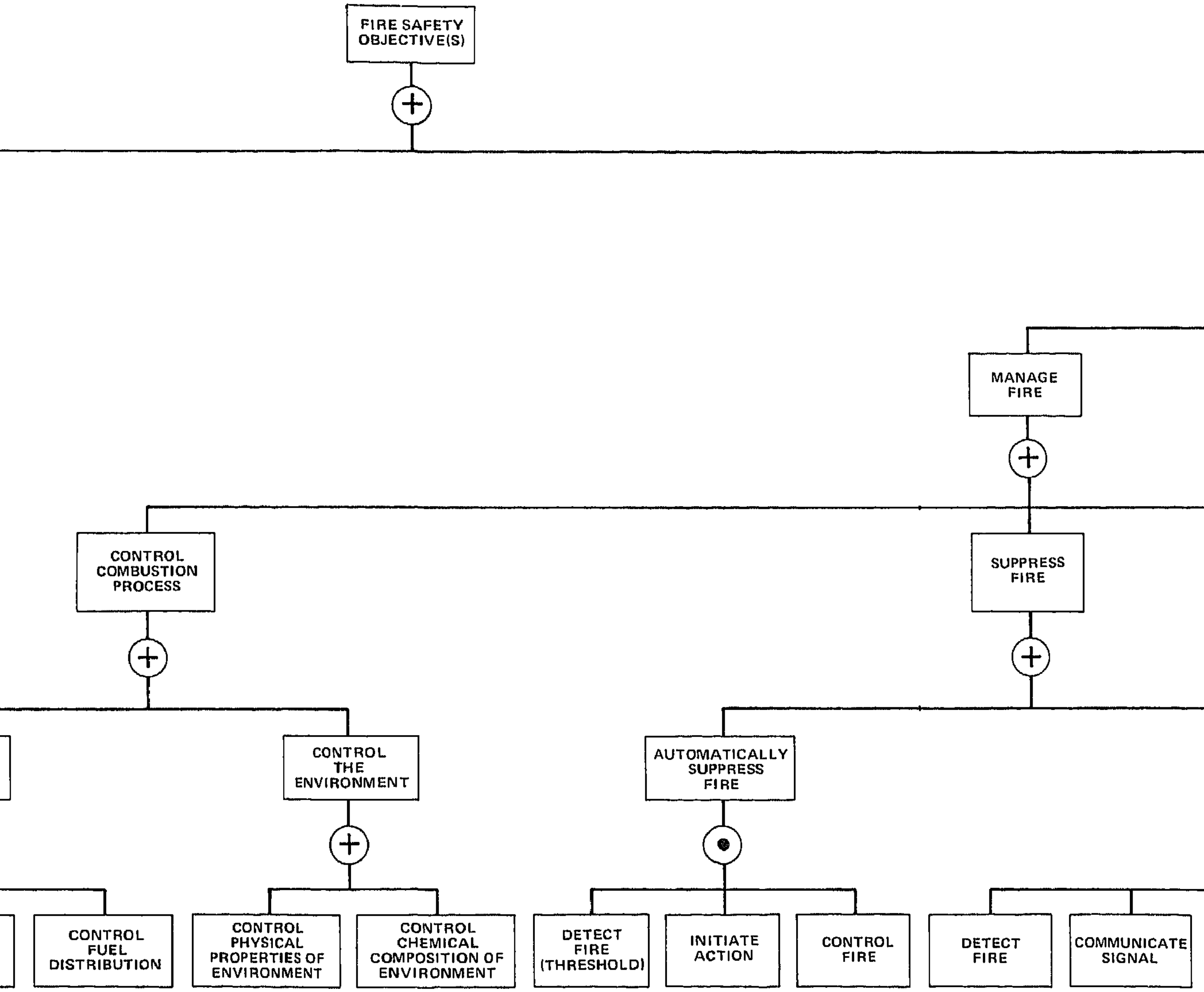


Figure A-4 Process Model for a Normal Distribution

APPENDIX B

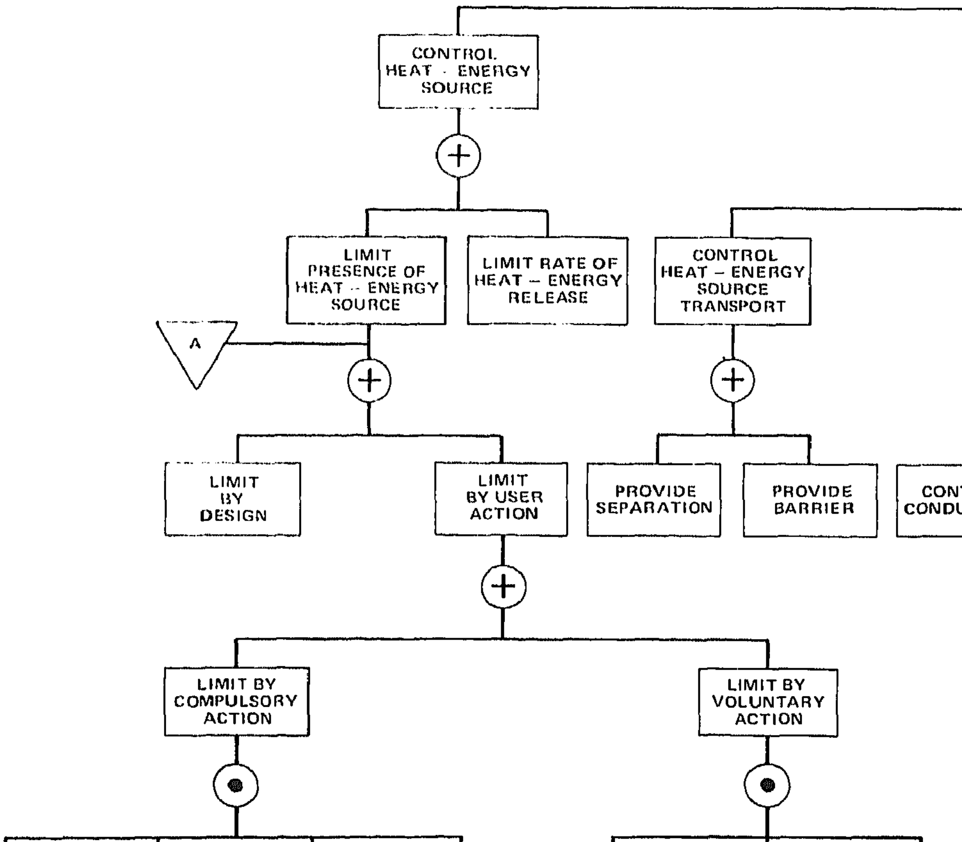
DECISION TREE



FIRE SAFETY OBJECTIVE(S)
MANAGE FIRE
CONTROL COMBUSTION PROCESS
SUPPRESS FIRE
CONTROL THE ENVIRONMENT
AUTOMATICALLY SUPPRESS FIRE
CONTROL FUEL DISTRIBUTION
CONTROL PHYSICAL PROPERTIES OF ENVIRONMENT
CONTROL CHEMICAL COMPOSITION OF ENVIRONMENT
DETECT FIRE (THRESHOLD)
INITIATE ACTION
CONTROL FIRE
DETECT FIRE
COMMUNICATE SIGNAL

DECISION TREE

Committee on Systems Concepts
for Fire Protection in Structures
November 1974



APPENDIX C

DISCUSSION OF INITIAL RESEARCH AREAS

DISCUSSION OF INITIAL RESEARCH AREAS

This section describes the major areas that were researched during the development of Building Firesafety Model. It is hoped that researchers doing similar work may be able to use the material presented here in order to prevent duplication of effort.

THE INVESTIGATIVE PROCESS

erature Search and Review

A literature search and review conducted through the NFPA technical rary was an initial research task. Combinations of key words in con- t (KWIC) were used in the search. The number of abstracts retrieved m each combination are included in Table C-1. Totals reflect net uments after elimination of duplicates.

In addition to a computerized literature search, considerable manual rch, including extensive review of NFPA library and staff-held docu- ts, was conducted. Through extensive screening, duplicates and irrel- nt items were eliminated and new documents added as they were identi- d and reviewed to form the Literature List in Appendix D.

One purpose of the literature search was to determine what research underway and what research had been completed in the fire area that ht assist in formulating the technical approach to this project. An- er purpose was to identify data and data sources that might be avail- e.

The literature search and the subsequent review of the documentation to several conclusions. One conclusion was that the method of ap- ach which used realm representations of fire growth is a reasonable . It was also concluded that considerable work which had been completed by y researchers , could be used to develop the fire and human response amics. In addition, it was observed that the properties of fire realms related processes such as products of combustion generation and spread, known to some degree although not completely determined. The most

Table C-1

Key Word Combinations Used in
Computerized Literature Search

Comprehensive Engineering Index	
Fire and protection and residen- or home or homes or building- or dwelling- or occupanc- or apartment-	114
Fire and protection and residen- or home or homes or dwelling- or occupanc- or apartment-	8
Fire and safety and model	0
Model or models or modeling and fire and protection and building-	6
Fire and protection and architect-	1
Fire and protection and systems analysis or system analysis	1
Radiant and fire and protection and residen- or home or homes or building- or dwelling- or occupanc- or apartment-	0
Delphi and model or models or modeling and fire	0
Fire and protection and design-	37
Fire and protection and design- and goal	0
Economic- or fire protection	3
System concept or systems concepts or systems concept and fire protection	0
Fatal- or injur- or property loss and fire	5
Fire and propagat- or growth and residen- or home or homes or building- or dwelling or occupanc- or apartmen-	1
Fire and safety or protection and urban and housing	0
Floor- or support- or wall or walls or partitions or column- and fire and test	11
Fire and test- and residen-	1
Flame and spread and residen- or home or homes or building- or dwelling- or occupanc- or housing	2
Hill (with) Burton and fire	0
Fire- and test- and fiberglass or FPR	1
Human and behavior and fire-	2
Risk and analy- and fire	0
Risk and analy- and residen- or home or homes or building- or dwelling- or occupanc- or apartment-	0
Smoke propagation or generation and residen- or home or homes or building- or dwelling- or occupanc- or apartment-	1
Reliability and smoke and detection	0

National Technical Information Service	
Fire and safety and econom-	25
Fire and safety and system- and concept-	4
Fire and safety and urban and housing	23
Fire and safety and design and model-	3
Fire and test- and column- or fire and test and support-	12
Fire and test- and floor-	13
Fire and test- and partition- or fire and test- and wall-	36
Fire and test- and residen-	42
Flame and spread-	11
Fire and safety and goal- or fire and safety and objectiv-	0
Fire and Hill and Burton	1
Fire and test- and honeycomb and struct-	8
Fire and human and behavior	7
Risk and analy- and building-	6
Fire and test- and sandwich and panel-	15
Smoke and detect- and reliab-	1
Fire and safety and apartment or dwelling or home	17
Fire and safety and apartment or dwelling or home, but not fire and residential	4
Fire prevention or protection and dwelling or apartment or home	5
Building and fire and model	20
Building and fire and radiat-	22
Building and fire and surviv-	3
Fire and decision and analy-	15
Fire and fiberglass or FRP and test-	8
Fire and propagat- and resident-	6
Fire- and fatal- and resident-	0
Fire and growth and time	2
Fire and hazard and resident-	1
Fire and injur- and resident-	0
Fire and injur- and apartment or dwelling or home	0
Fire and property and loss	0
Fire and prevention or protection and automat-	16
Fire and safety and architect-	3
Fire and safety and case and stud-	2

of theoretical and empirical studies on the processes of fire and fire safety, there is, at present, no means for unifying all this material in a format wherein accurate estimations of fire development for all possible scenarios can be made. It is recognized that the Decision Tree provides a degree of that unification and can serve as a basic underlying logic.

As a result of this research, a method for evaluating fire safety in buildings which included what is known about the process involved was developed. If a process was well defined, that information was included in the method and labeled as known. If a process was not well understood, then assumptions concerning the process were made and included in the model, but clearly identified as to the source and reliability of the estimations. This evaluation led to the formulation of the approach to the problem as described in this report.

Decision Tree Coding

Coding the Decision Tree in some logical manner in order to facilitate direct application of the Tree was one of the initial research tasks. The coding scheme was designed to be compatible with the state transition model. Each DT element was given a unique code which described the position of the element, the type of FSOC it affected, how much the MPS affected the element, and what type of data (fact, theoretical, judgement, or opinion) was used to obtain inputs for this element. This scheme al- allowed the Tree to be accessed by a computer program. For details, see Figure C-2.

. The coding scheme presented herein is designed to expedite the analysis, and be compatible with the state transition model. It treats each element of the Decision Tree in a unique manner and can be extended down any branch by merely adding number codes to the right as long as there are no more than nine input elements per level. It has been extended to 12 levels which, in all likelihood, will involve particular devices. It is planned that the analytical or simulation modeling will be done in FORTRAN IV on the NFPA IBM 370/125.

. The scheme is as follows:

a. Success Evaluation Factors (digits 1, 2, 3, 4)

X,000 — General Fire Safety Objective Component

X,XX0 — Critical Event (realm transition point)

X,XXX — Location of Threatened person(s) or property

b. Element Identifier (Digits 5-16)

(1) A 12 digit Element Identifier for each element on the decision tree with each digit defined as follows:

X00,000,000,000 — 0 to signify an "And" Gate and 1 to signify an "Or" Gate of the element identified.

XX0,000,000,000 — Prevent or Manage Impact (level 2 blocks*)

XXX,000,000,000 — level 3

⋮

XXX,XXX,XXX,XXX — level 12

---

*All elements numbered sequentially from left to right for each branch at each level.

(2) Examples:

	Success Evaluation Factors
Automatically Suppress Fire	X,XXX,121,210,000,000
	OR Gate
Vent Fire	X,XXX,121,311,000,000
Provide Pre-Ignition Instructions	X,XXX,122,221,310,000
Defend Against Smoke and Gas Intrusions	X,XXX,022,212,122,000

c. HUD/MPS Field Evaluation (digits 17 through 29)

(1) Digit 17 - Impact Identifier for the General Firesafety Objective Component (FSOC) given in position 1, coded as follows:

0 - does not apply to this element for this FSOC
1 - (not used)
2 - applies directly to this element for this FSOC
3 - (not used)
4 - generally applies to this element for this FSOC
5 - (not used)
6 - peripherally or remotely applicable to this element for this FSOC
7 - (not used)
8 - might apply, definition unclear
9 - (not used)

(2) HUD/MPS Reference Sentence (digits 18-29)

Example 1: 507-6.1 Bulk Sealing Compound

coded 0507-06-01-00-00

Example 2: 507-6.1.f. Polyurethane Compounds (Polyurethane Prepolymers)

coded 0507-06-01-00-06 (f is the sixth letter in the alphabet and the last digit in this coding scheme)

d. Success Probability Estimate (digits 30-41) - probability estimate for Factors given in 1 through 4 for element shown in 5 through 16.

Probability may be computed (estimated for the HUD/MPS) for Factors in 1, 2, 3, 4. If it meets the HUD/MPS, what is the probability of success for this Factor? For example: 99.9990000000.

e. Confidence Levels (Digits 42 and 43). These will designate the source and, thereby, a measure of the level of confidence in the quality of the data.

00 Laws of Science

01 Fundamental theories founded in a high level of scientific evidence

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.
.

04 Theories long accepted and applied in fire protection field with no evidence of disproof

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.

10 Data-Based Information

11 From fire loss data - verified and unbiased
12 From fire loss data - believed to be unbiased (not verified)
13 ....

.
.
.
.

19 From fire loss data - believed to be biased and unconfirmed, but "all we've got"

20 Fire Test Results

21 From fire test data - sound, reproducible results
22 ....

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29 From fire test data - abstract and questionable conclusions, not reproducible

30 Emperical Testing/Data

31 ....

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40 <u>Professional Judgement</u>

41 Judgemental - a representative, unbiased cross-section of fire protection practitioners and results "averaged" via.... (method)

42 ....

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48 Judgemental - a single fire protection practitioner surveyed - one considered "qualified" in scope of the question

49 Judgemental - a single fire protection practitioner surveyed - one not specialized in the subject in question

50 ....

51 ....

60 <u>Nonprofessional Opinion</u>

60 Judgemental - a sampling of a cross-section of society was surveyed without bias

61 ....

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69 Judgemental - a single "citizen on the street" randomly interviewed

70 ....

71 ....

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ean Indicated Cut Sets (BICS)

As part of the study of the Decision Tree, the logic of the Tree analyzed using a logic called "cut-set" adapted from the work of ow and Chatterjee.[11] A cut-set is a set of basic conditions (Tree ents) whose occurrence implies success in meeting the goal, i.e., firesafety objectives. These cut-sets are known as Boolean Indi- d Cut Sets (BICS). A cut-set is called minimal if the number of ents cannot be further reduced and still insure goal achievement.

The BICS were determined for the Decision Tree and, from that anal- , the logical consistency and lack of redundancy in the Tree was irmed. In a logically consistent tree, each branch of elements (under able conditions of other branches) can influence the outcome element. , the application of the BICS helped the project staff understand logic of the DT, gain confidence in the soundness of the Tree, and v an examination of the firesafety implications of grouped elements S). The BICS may again prove useful when the Tree has been modified eflect the effect of Tree elements or combinations thereof on FSOC he various fire realms.

APPENDIX D

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